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LIGHTWEIGHT GEARBOX DEVELOPMENT FOR PROPELLER GEARBOX SYSTEMS APPLICATIONS POTENTIAL COATINGS FOR TITANIUM ALLOY GEARS

Richard A. Hirsch

General Motors Corporation

Prepared for:

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December 1972

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R. A. Hirsch

Detroit Diesel Allison Division
General Motors Corporation
Indianapolis Operations

TECHNICAL REPORT AFAPL-TR-72-90

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Air Force Aero Propulsion Laboratory
Air Force Systems Command
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Optimum titanium material composition was selected to provide desirable strength properties and compatibility to the selected surface coating system. Plated surface coatings, bonding techniques, heat treat processes, and surface lubrication coatings were investigated to provide an optimum system which would withstand the scheduled test requirements. Iron-plated coatings which were diffusion bonded to the titanium core and then carbonitrided to provide surface hardness were selected as the most promising system.

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Three sets of test gears were designed and manufactured utilizing the developed system. Experimental evaluation of the test gears established their 10^7 cycle surface contact fatigue strength (based on steel modulus of elasticity) at: Phase I 96,000 psi Phase II 120,000 psi Phase III 152,000 psi.

Secondary goals of oil starvation, oil contamination, and full-scale endurance tests were not accomplished in order that process development could be continued to improve the small scale gear strength.

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I C

FOREWORD

This final technical report was prepared by Detroit Diesel Allison Division, (DDA), of General Motors Corporation, Indianapolis, Indiana, under USAF Contract F33615-70-C-1383. The contract was initiated under Project No. 3066, Task No. 306612. The contract was administered by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Mr. M. P. Wannemacher, (AFAPL/TBP) was Project Engineer for the Air Force.

Mr. R. A. Hirsch, Section Chief, Mechanical Technologies, was Program Manager at DDA for the project. Acknowledgment is made to the many contributors within DDA, especially J. A. Burger, J. F. Kildsig, L. W. McBride, Q. O. Shockley, P. L. Colcord, F. K. Lea, and M. R. Chaplin.

This report covers the development of coated titanium gears from February 2, 1970 to September 1, 1972, and is assigned DDA supplementary report number EDR 7326.

This report was submitted by the author December 1972. Publication of this report does not constitute Air Force approval of the reports findings or conclusions. It is published only for the exchange and stimulation of ideas.

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The objective of this program was to develop the capability of titanium gears to sustain 126 million repetitive stress cycles at a surface contact stress of 132,000 psi (based on steel modulus of elasticity). The achievement of this goal will make titanium gears significantly attractive for the 1975 time period.

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SYMBOLS

Sc	-	Calculated hertzian stress, psi
μ	-	Poisson's ratio
E	-	Young's modulus of elasticity, psi
W_t	-	Tangential load, lb
ϕ	-	Pressure angle at the operating pitch diameter
Fe	-	Effective face width, in.
R_g	-	Gear pitch radius, in.
R_p	-	Pinion pitch radius, in.
TQ	-	Torque, lb in.
Sb	-	Calculated bending stress, psi
Dv	-	Stress parabola vertex
F_{min}	-	Minimum face width
X_{HPSTC}	-	X factor calculated from high point of single tooth contact

SECTION I

INTRODUCTION

Future technology has established the need to consider the weight savings that could be achieved if high strength-to-weight ratio materials could be used in aircraft gear applications. The weight advantage and versatility of titanium establishes it as a desirable gear material if its contact surfaces could be conditioned to withstand the high unit loading required for gear teeth. Prior Military funded projects since 1954 have advanced the potential of satisfactory operation of titanium gears up to the operating level of approximately 112,000-psi hertzian contact stress. Present hardened steel gears have a comparable stress capability between 180,000 to 242,000 psi at 10^7 cycles.

Detroit Diesel Allison (DDA) has completed a 30-month development program in which iron coated gears were developed and tested on a Ryder gear test rig. The program was divided into three phases with the concluding test gears achieving a stress level of 152,000-psi hertzian contact stress.

The success of this program presents a technological advancement toward the ultimate goal of replacing steel gears with reduced weight components.

SECTION II

TECHNICAL DISCUSSION

TITANIUM ALLOY SELECTION

Published information related to the use of titanium alloys as a gear material revealed the importance and necessity for a suitable combination of a high strength base alloy, and the coating system. The selection of the titanium alloy had to be capable of developing base metal strength properties and at the same time the heat treatments required for these properties must be compatible with the processing parameters for applying the coating system.

The design criteria used for selecting a titanium gear alloy was similar to the selection process used for carburized and/or nitrided steel gears; since the requirements for the titanium material should be very similar to that of the steel gear material. Both require a high yield strength with good fatigue life to resist excessive tooth bending.

It was preferable that the titanium gear core material exhibit a hardness of R_c34 minimum to reduce the hardness gradient between coating and core and to present a core relationship similar to that of steel gears.

The titanium material was required to have good hardenability and provide adequate strength for coating support regardless of section size.

The proposed surface hardening procedure and optimum core property development temperature should be compatible.

The ability of the alloy to accept the coating was believed to be of paramount importance; however, in the selection of a titanium alloy there appeared to be no great difference in coatability of the materials considered. Other properties that could influence material selection are density, modulus of elasticity, Poisson's ratio, and thermal conductivity.

After considering the basic requirements for a titanium gear material, it becomes apparent that the alloys closest to meeting these requirements are the high strength alpha-beta titanium alloys such as:

- Ti 6Al-4V (AMS-4928)
- Ti 6Al-6V-2Sn (AMS-4971)
- Ti 6Al-2Sn-4Zr-6Mo
- Ti 6Al-5Zr-4Mo-1Cu-0.2Si (IMI Ti 700) (EMS-59030)

Composition of these alloys is shown in Table I.

Table I.

Composition of titanium alloys.

Element	Composition percent by weight			
	Ti 6-2-4-6*	Ti 6-4**	Ti 6-6-2†	EMS-59030‡ IMI 700
Aluminum	5.5-6.5	5.50-6.75	5.00-6.00	5.00-7.00
Tin	1.8-2.2	---	1.50-2.50	---
Zirconium	3.6-4.4	---	---	4.00-6.00
Molybdenum	5.5-6.5	---	---	3.00-5.00
Vanadium	---	3.50-4.50	5.00-6.00	---
Copper	---	---	0.35-1.00	0.50-1.50
Iron	0.15 max	0.30 max	0.35-1.00	0.20 max
Silicon	---	---	---	0.10-0.50
Carbon	0.04 max	0.10 max	0.05 max	0.15 max
Oxygen	0.10 nom	0.20 max	0.20 max	---
Nitrogen	0.02 max	0.05 max	0.04 max	---
Hydrogen	0.015 max	0.0125 max	0.015 max	0.013 max
Other elements	---	0.40 max	0.40 max	---
Titanium	Remainder	Remainder	Remainder	Remainder

*Ti 6Al-2Sn-4Zr-6Mo

**Ti 6Al-4V (AMS-4928)

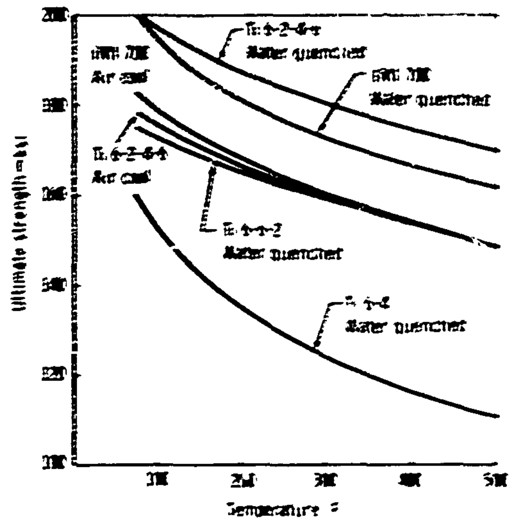
†Ti 6Al-6V-2Sn (AMS-4971)

‡Ti 6Al-5Zr-4Mo-1Cu-0.2Si (IMI 700) (EMS-59030)

These materials exhibited ultimate strengths of 140,000 to 160,000 psi in the solution treated and 190,000 to 200,000 in the aged condition.

The coatability of the listed alloys is essentially the same, however, the compatibility of the base metal heat treatment and coating heat treatment can vary and is of great importance. If the alloy is to be used in the solution heat treated and aged condition, then the greatest flexibility and strength response can be achieved with the alloys that are capable of being air-cooled from the solution treating temperature. This would allow a marriage of the solution heat treatment and coating thermal treatments without the need for an integral rapid quench facility. It also minimized distortion and residual stresses caused by rapid quenching. With such a material a selected coating treatment in the range of 1550 to 1650°F would also serve as the solution treatment of the titanium alloy; any treatment below 1100°, i.e., nitriding, could be done within the aging treatment or after the aging treatment.

A comparison of tensile properties is shown in Figures 1 and 2 which show that the air-cooled alloys fall into a respectable strength range. The air-cooled Ti 6Al-2Sn-4Zr-6Mo and the air-cooled IMI Ti 700 develop ultimate strengths of 175,000 psi or above at room temperature. In turn, the fatigue properties as shown in Figure 3 indicate that there is very little difference in the fatigue strength of the water quenched and air-cooled Ti 6Al-2Sn-4Zr-6Mo and IMI Ti 700. As shown, both of these alloys have substantially higher fatigue strengths than Ti 6Al-4V or Ti 6Al-6V-2Sn.



All alloys are in the solution treated and aged condition.

*All alloys are in the solution treated and aged condition.

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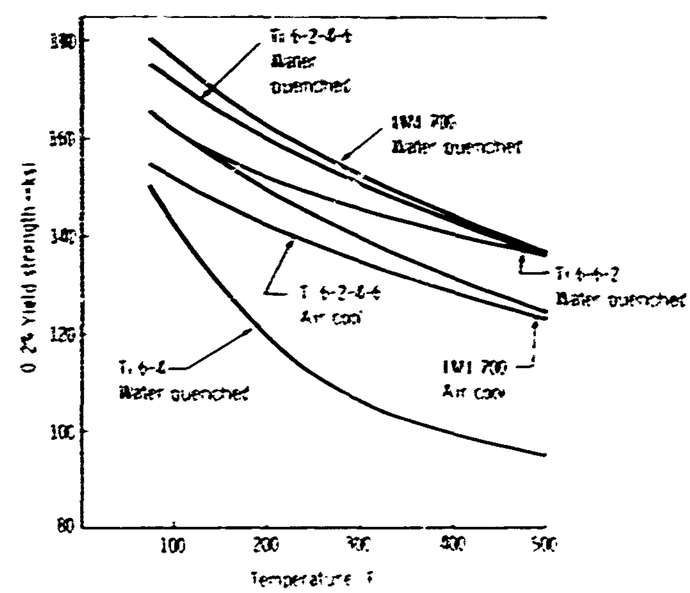
Figure 1. Comparison of minimum tensile ultimate strengths at various temperatures.

All alloys are in the solution treated and aged condition.



*All alloys are in the solution treated and aged condition

7326-3

Figure 2. Comparison of minimum 0.2% yield strengths at various temperatures.

Figure 4 shows the material strength as related to section thickness and hardenability. Ti 6Al-2Sn-4Zr-6Mo and IMI Ti 700 are the best; the water-quenched material would result in also having a higher surface hardness. The lower surface hardness of the air-cooled material is more than offset by the flexibility achieved in heat treating and the more uniform property gradients.

The other important properties, i.e., density, modulus of elasticity, Poisson's ratio, and thermal conductivity are physical properties that are not affected by mechanical or thermal treatments but only dependent on chemical composition. In comparing these properties for Ti 6Al-2Sn-4Zr-6Mo and IMI Ti 700 there is essentially very little difference.

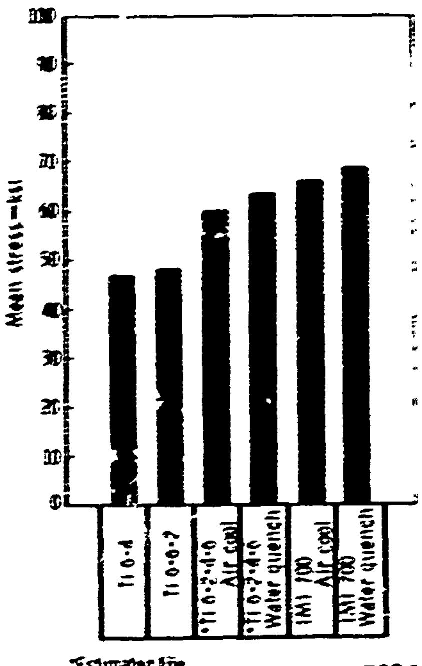


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Figure 3. Comparison of 10^7 fatigue strength.

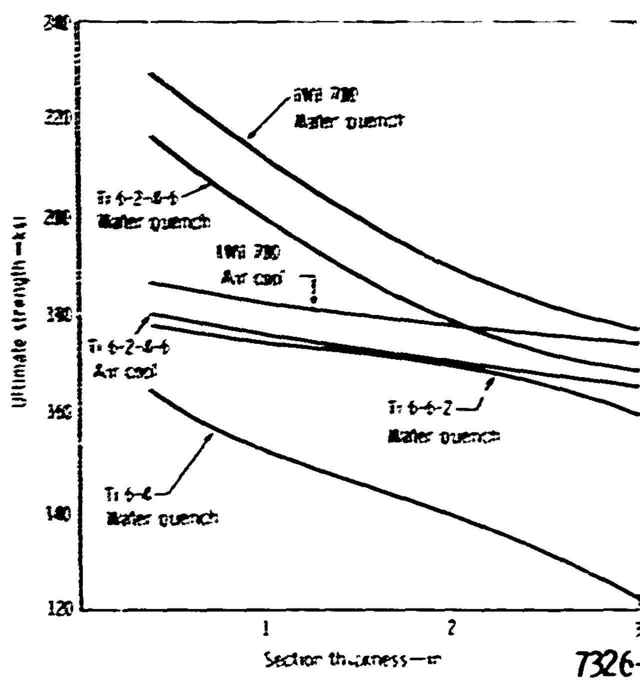

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Figure 4. Fatigue strength vs section thickness and hardenability.

The selection then becomes a choice between air-cooled Ti 6Al-2Sn-4Zr-6Mo or the higher strength IMI Ti 700. The air-cooled Ti 6Al-2Sn-4Zr-6Mo was selected for this gear program since DDA experience has shown that the IMI Ti 700 material was difficult to procure within the United States.

To obtain the necessary coating properties, i.e., carbonitrided case hardness and structure, the processing sequence was altered and this precluded obtaining maximum base material strength and hardness properties. The ultimate and yield strength values for the Ti 6Al-2Sn-4Zr-6Mo core, although reduced, did provide a gear of moderate to high strength comparable to steel gears. Additional processing development was investigated to produce gears which would incorporate full aging of the core to full strength, and at the same time allow full case hardening heat treatment. Although this end was not fully realized, core strength improvements through complex heat treat cycles, were accomplished.

HARD SURFACE COATING

The original concept of providing a wear surface for titanium gears included the application of "hard" coatings based upon the codeposition of refractory and hardening agents in iron and nickel matrices, e.g.,

Fe - C	Ni - C
Fe - S	Ni - TiC
Fe - TiC	Ni - BN
Fe - BN	Ni - S
Fe - B	
Fe - Si	

Previous work had indicated a capability for applying thin coatings (less than 5 mils) of these materials. As the gear design portion of the program developed, however, a finished hard coating thickness of 12-13 mils was specified for gear surfaces. It soon became evident that these "dirty" electrodeposits of iron and nickel would not be satisfactory. The nonmetallic inclusions promoted nodular and porous deposits after a few mils of plating and could not provide a dense, high strength structure suitable for the gears as more material was deposited.

The hard surface coating systems selected on the basis of their potential for development into satisfactory gear surface materials were:

- Electroless nickel (GM Nichem)
- Electrodeposited iron-nickel (hardened)
- Electrodeposited iron (hardened)

Electroless Nickel (GM Nichem) Coating

Prior to this program, DDA had considerable background in the application of the low phosphorous, electroless nickel coatings to titanium alloy surfaces. This experience was limited to thin coating thicknesses applied on flats, cylinders, splines, and gear configurations. This technique also had been successfully used as a method for providing a bonding agent in preparation for applying other bonded coatings to titanium alloy surfaces.

The technique for applying GM Nichem consists of abrasive wet blasting the titanium alloy surface with clean, fine grit silicon carbide and immersion of the wet article in the plating bath with an applied DC current for the initial two to three minutes. The plated article is then heat treated in vacuum at 1000°F for four hours.

Thin coatings (0.1 to 0.3 mils) produced in this manner are suitable after proper activation as a base for the application of other electrodeposited materials. Thicker coatings produced in the same manner have a hardness of Rc55 to 58 and are good oxidation, corrosion, and wear-resistant coatings. These electroless nickel coatings can be plated to have good surface finishes in thicknesses up to three or four mils. Thicker coatings can be finish ground to size using grinding procedures similar to those used for finish grinding hard chromium deposits.

The GM Nichem plating process was used for applying coating thicknesses of up to 24 mils to test specimens. Bonding to the titanium alloy was accomplished by a vacuum heat treatment at 1000°F, followed by a slow cool to room temperature. This procedure proved adequate for the Tribometer and three-ball-and-cone test specimens and resulted in surface hardnesses of Rc55 to 58 after final grinding.

Identically processed test gear tooth surfaces developed thermal cracks during the postdiffusion cooling or during subsequent final grinding operations.

The use of glass bead peening was implemented to induce compressive surface stresses and thereby reduce the cracking tendency of the Nichem plate. Glass bead peening was used subsequent to the elevated temperature diffusion cycle (1000°F) and subsequent to each grind operation. Although glass bead peening measurably reduced the cracking tendency, the condition could not be eliminated. Because of this condition, further heavy Nichem plate development on gears was suspended. Furthermore, in the initial efforts to bond iron and iron-nickel electrodeposits to the titanium alloy test specimens, an electroless nickel coating 0.1 to 0.2 mil thick was used. The thin Nichem coatings, processed and vacuum heat treated (as previously described) were lightly fine grit wet blasted and electrochemically activated prior to immersion in the iron and iron-nickel plating solutions. This system worked well until the higher temperature heat treatments and rapid quenches were used. At this time it was learned that the diffused Nichem would not withstand the thermal shocks.

Electrodeposited Iron-Nickel Coating

Extensive investigations by the General Motors Research Laboratories have shown that the presence of nickel in a 3 to 5% concentration does improve the hardenability of iron deposits. Very satisfactory deposits having good hardenability were plated on the regular sections of the Tribometer and three-ball-and-cone test specimens. However, plating of the Ryder test gear teeth presented a problem in that nickel rich deposits separated from the iron and were preferentially deposited on the gear tooth flank areas as shown in Figure 5.

Efforts to overcome this problem by adjustments in current density, temperature, and nickel concentration were not successful. It was believed that this problem probably could be solved by using a large volume plating tank which would permit greater anode-to-cathode distances, more stable electrolyte parameters, and use of cathode shielding and/or auxiliary anodes.

A large plating tank facility was established and although some improvement in uniformity of Fe-Ni plating in low current density areas was seen, it was not sufficient. Iron-nickel plating was curtailed in favor of electro-deposited iron coating.

Electrodeposited Iron Coatings

Electrodeposited iron is an attractive, low-cost metal for building up thick coatings having relatively good strength. It is also possible to heat treat electrodeposited iron and provide acceptable hardness characteristics. The iron plating process yielding the best results was from a conventional ferrous chloride-calcium chloride solution referred to as the Fisher-Langbein Solution and the General Motors Research iron plating process covered by U.S. Patent 3,404,074. The plating tank used for this development is shown in Figure 6.

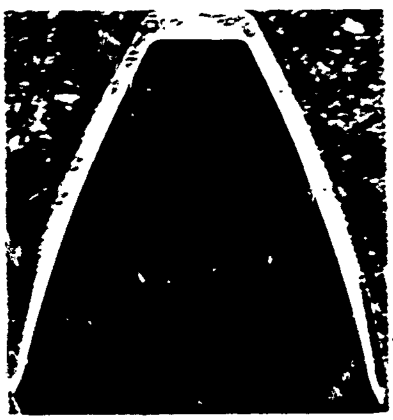

Figure 5. Iron-nickel alloy segregation in tooth flank.

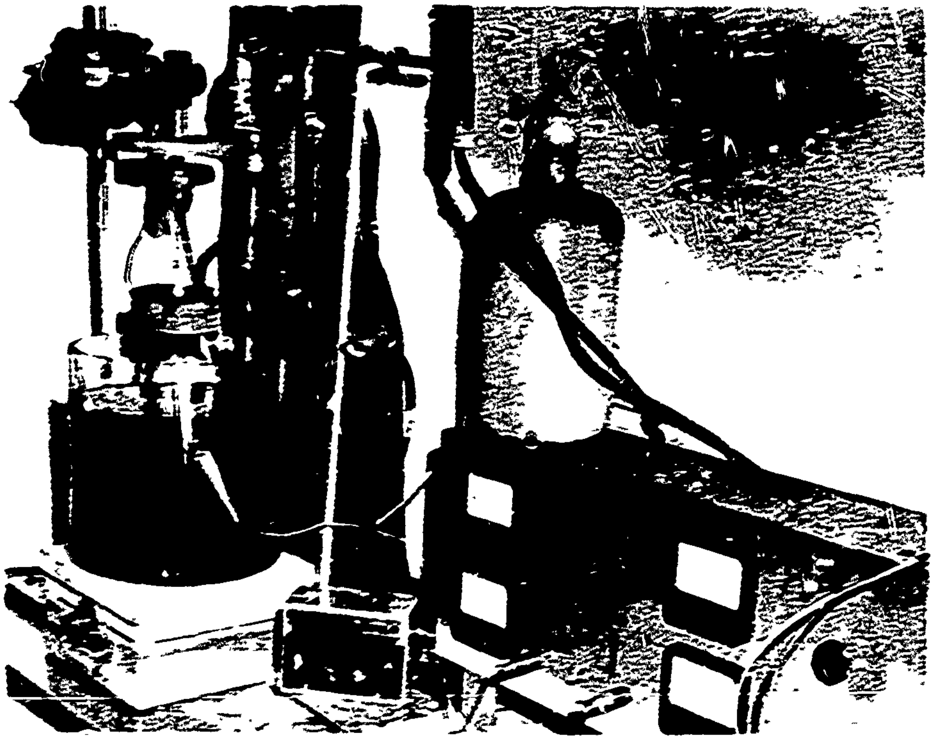

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Figure 6. Small volume plating tank.

Results of work completed, while iron plating various gear configurations, led to the conclusion that acceptable uniform thick deposits of iron and/or iron-nickel deposit were not attainable on gear teeth by ordinary plating procedures. As a result of this observation, three different techniques for plating the gears were explored as follows:

- Use a large tank where the anodes can be located at considerable distances from the surfaces to be plated.
- Use various masking fixtures designed to aid in equalizing the plating distribution over the gear surfaces.
- Use insoluble auxiliary anodes located near the gear root surfaces.

Since plating accomplished in small volume plating tank had demonstrated unsatisfactory "throwing power" to plate into recessed surface areas of the gear teeth, it was decided to try a large volume tank where the anode to cathode distance would be relatively large in comparison to that obtained in the small volume baths.

The enlarged plating system shown in Figure 7 consists of a 200 gal polypropylene lined tank with an acid resistant pump and filter unit. Four thermostatically controlled electric quartz immersion heaters maintain solution temperature and the unit is equipped with an oscillating rod cathode agitator and impeller solution agitation.

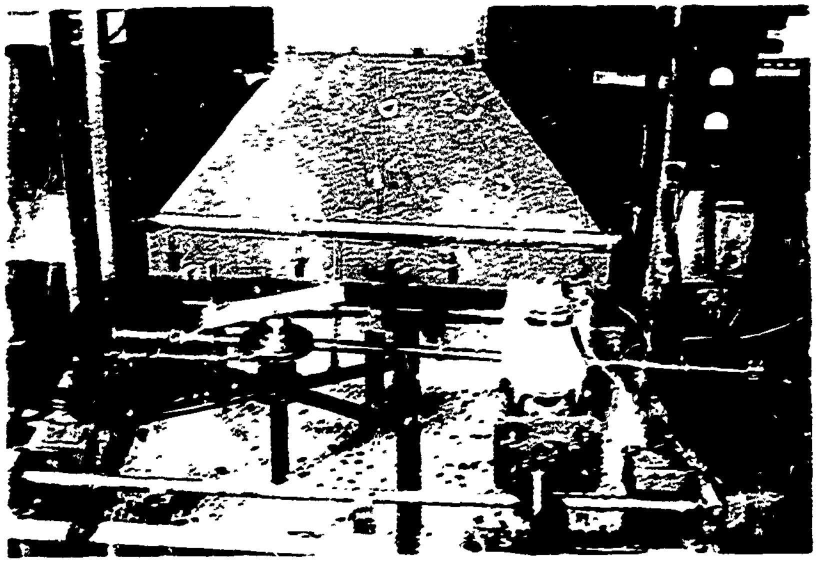

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Figure 7. Large volume plating tank.

The surface of the solution is covered with polypropylene balls to reduce evaporation and thermal losses.

The tank was filled with GMR Iron Plating Solution (U.S. Patent 3,404,074) which is nominally as follows:

Ferrous chloride	465 gm/l
Ferrous iron	205 gm/l
Dispersant additive	1 gm/l
pH	0.5
Temperature	190°F
Anodes	Armco iron

It was believed that the greater anode to cathode distances obtainable in the large tank system would equalize the plate thickness over the gear surfaces. While there was some small improvement as compared to the small tank plated gears, the plating distribution was considered to be unsatisfactory. A PR (periodic current reversal) control unit was added to the plating current system and periodic reversal current procedures were tried without any appreciable improvement in plating distribution being noted. It was hoped that PR processing would reduce the excess plate from the pitch line outward while at the same time permitting greater deposition in the gear root area.

Auxiliary anode plating feasibility was tested by fabricating a fixture, Figure 8 which provided the auxiliary anoding on a gear segment. Insoluble auxiliary anodes were fabricated from platinum pins placed parallel to the root surfaces 1/8 in. from the root surfaces. Addition of the auxiliary anodes appeared to provide additional plate to the root surfaces and was deemed sufficiently promising to warrant additional testing.

By varing the anode to root distances, plate depths of 0.008 to 0.021 in. were obtained. Although auxiliary insoluble anodes were found to be helpful in depositing iron in the gear root areas, use of the fixture was found to be too difficult to control. As the plate depth built up, one or more of the anodes would short out due to misalignment or more rapid deposition in the immediate area causing the whole auxiliary anode unit to malfunction and cease plating in the root area. For these reasons the use of auxiliary anodes for this application was deemed unusable.

At this stage of plating development, the difficulty preventing attainment of a satisfactory plated gear was lack of sufficient plating thickness in the root area of the gear. Up to this time all plated gears had shown excessive build-up from the pitch line outward which resulted in large nodules at the OD of the gear teeth. While this was occurring the gear root surfaces were still deficient in plating thickness. Extended plating time, up to 32 hr, was of little help, since the nodules grew larger with little improvement in root plate thickness. It was concluded that the formulation of the large nodules was the principle reason for the deficient plating thickness being obtained in the root area due to the fact that the nodules were serving to shield and rob the rest of the gear during the plating cycle. To remedy this situation, it was decided to use the "through-the-window" plating principle.

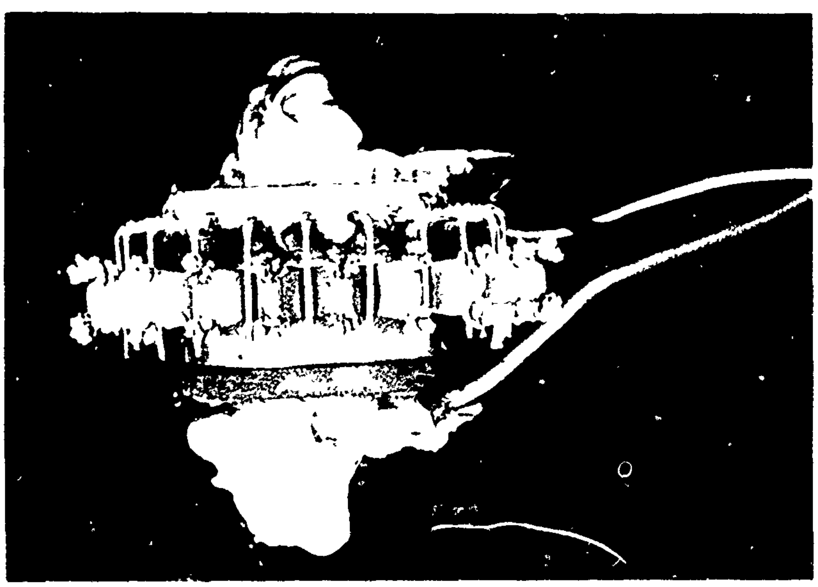

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Figure 8. Auxiliary anode plating fixture.

Several through-the-window plating masks and fixtures were built and tested. The first one was fabricated from filled silicone rubber and was made to fit and plate a 36 tooth gear. This mask, Figure 9 was fabricated so that the effective window location was centered over the gear tooth space with 0.125 in. clearance above the root surfaces. Plating accomplished with this mask was more uniform in plate thickness than was obtainable by prior methods. The plate depth at the tooth pitch line of 0.022 in. resulted in a plate depth of 0.011 in. at the root in a 24 hr plating period.

The second mask was fabricated from Micarta to fit a 21 tooth gear. This mask was designed similar to the rubber mask except the effective window opening was located with 0.188 in. clearance above the root surfaces.

Gears plated with this mask were unsatisfactory because most of the plating occurred on the upper half of the teeth while very little plate was deposited on the root surfaces. Results of the test indicated the effective window opening was too far away from the root surface.

The third mask, Figure 10, was fabricated from Micarta with 21 gear tooth form spaces which provide 0.070 in. clearance with the gear teeth. The window openings were again located just opposite the root fillet area. Plating with this mask was unsuccessful because the clearances were too close, allowing plating buildup to contact the mask and made it difficult to remove the gear from the mask.

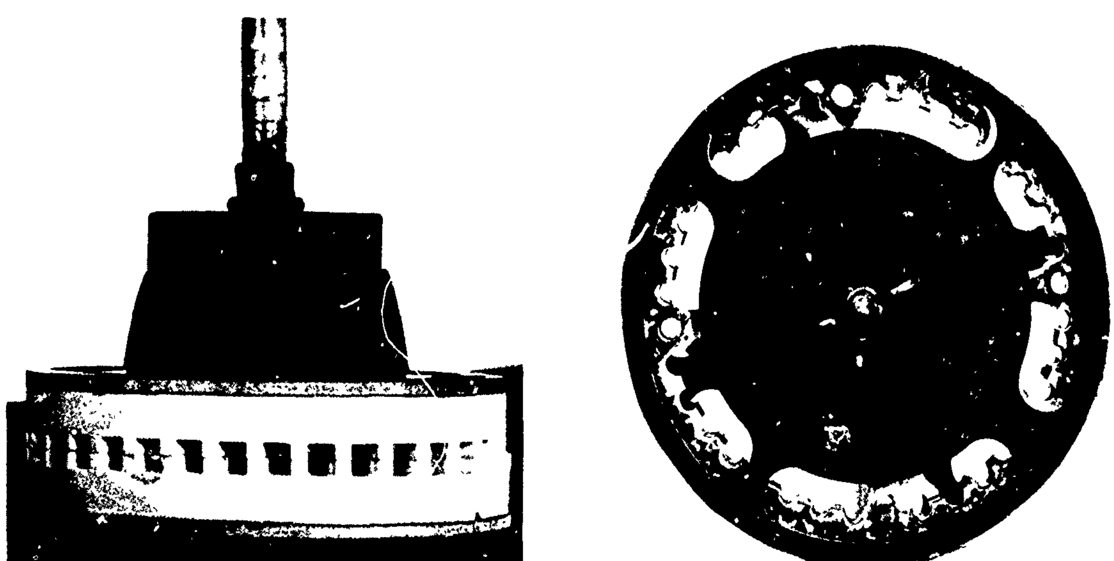

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Figure 9. Silicone rubber plating mask.

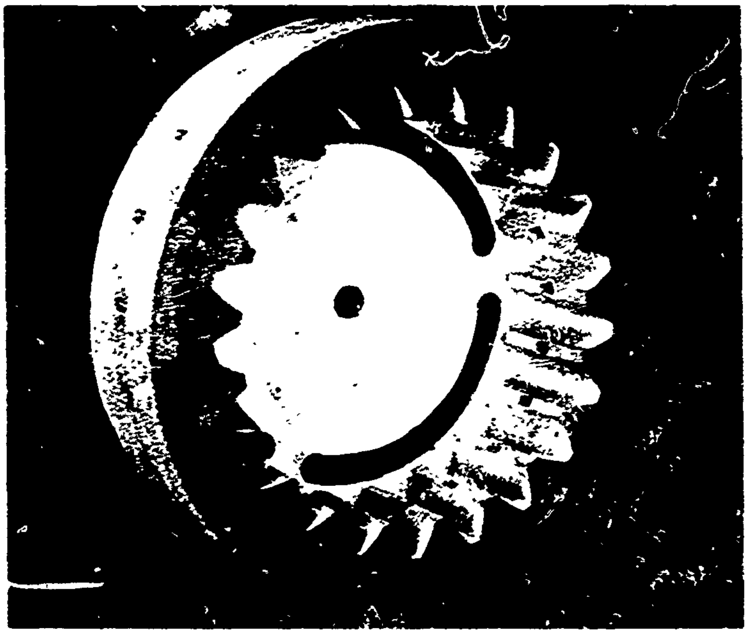

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Figure 10. Micarta mask with gear tooth form spaces.

The fourth mask was fabricated from Micarta to fit a 21 tooth gear. The mask differed from the previous ones in that the effective window openings are located beyond the OD of the gear.

The window slots of this mask were much longer than those of the previous masks. Several plating runs were made with this mask with the slot openings ranging from full open to very small openings. The mask side opening vents were also varied in size to determine proper size necessary to produce the desired web plate thickness. Figure 11 shows this mask and Figure 12 the optimum gear plated with restricted slot openings with 0.010-in. plate thickness.

The fifth Micarta mask was fabricated using the design configurations found to be most successful when using the adjustable slot mask.

Figure 13 shows the mask and Figure 14 the optimum gear plated with 0.015 in. min plate thickness.

The sixth and final mask which incorporates the optimum features of the earlier development masks is shown in Figure 15 and the optimum plated mask. The final optimum gear with 0.018 in. min plate thickness is shown in Figure 16.

Plating procedure and parameters were as follows:

1. Degrease

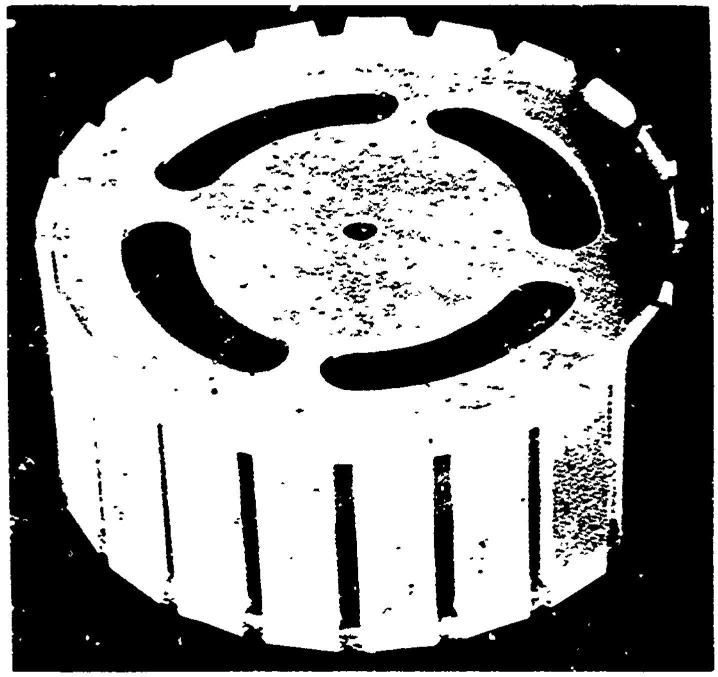

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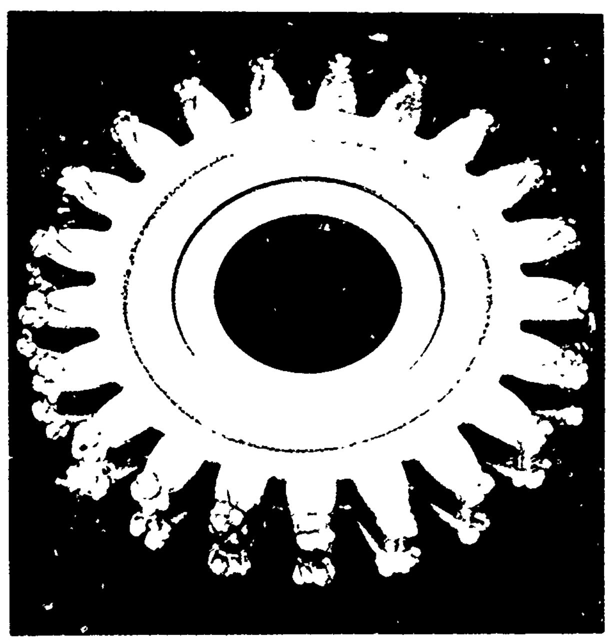
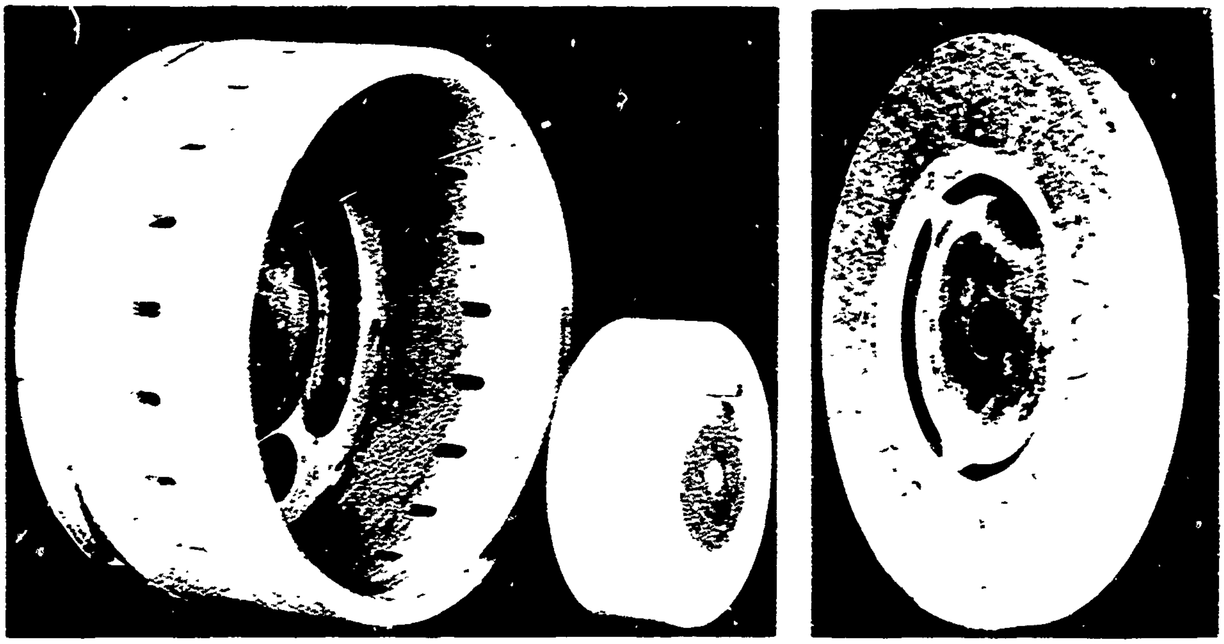
Figure 11. Mask with adjustable slot sizes.



7326-13

Figure 12. Gear plated in adjustable slotted mask (0.01-in. plate thickness).



7326-14

Figure 13. Fifth plate mask.

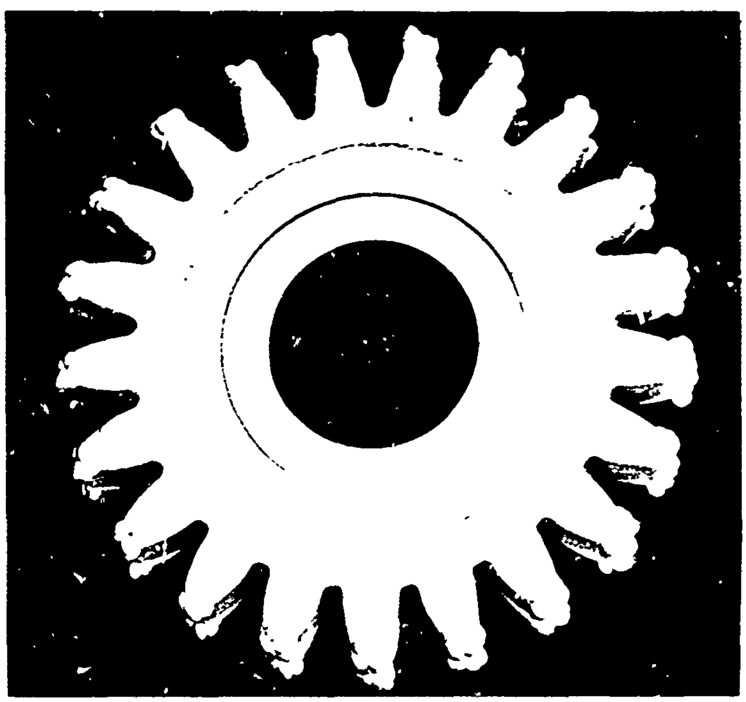


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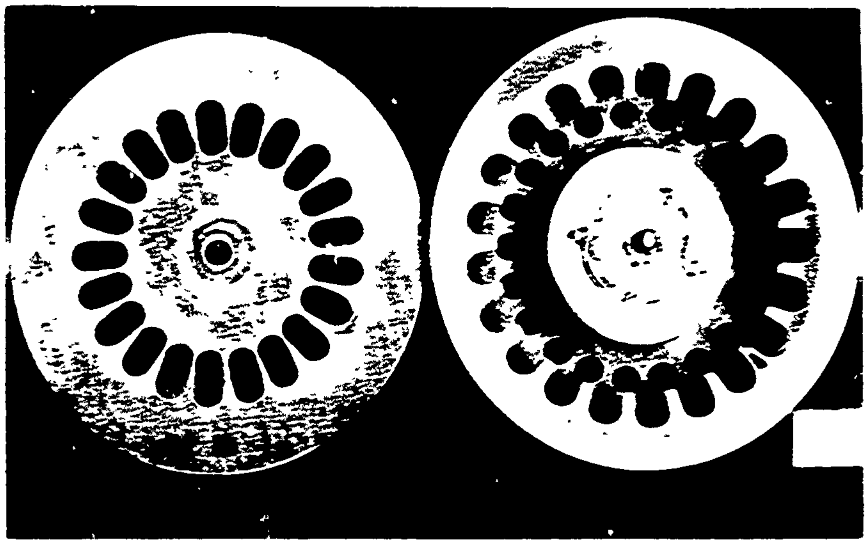
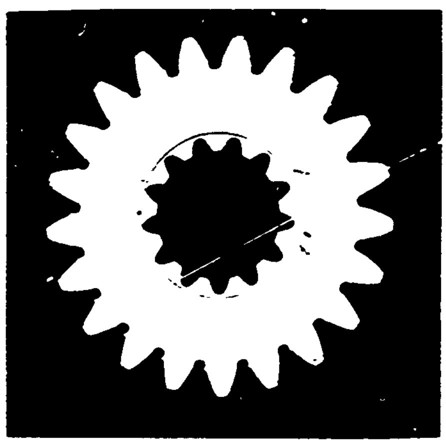
Figure 14. Gear plated in fifth mask (0.015-in. plate thickness).



7326-16

Figure 15. Optimum plating mask.



7326-17

Figure 16. Final optimum plated gear.
(0.018-in. min plate thickness)

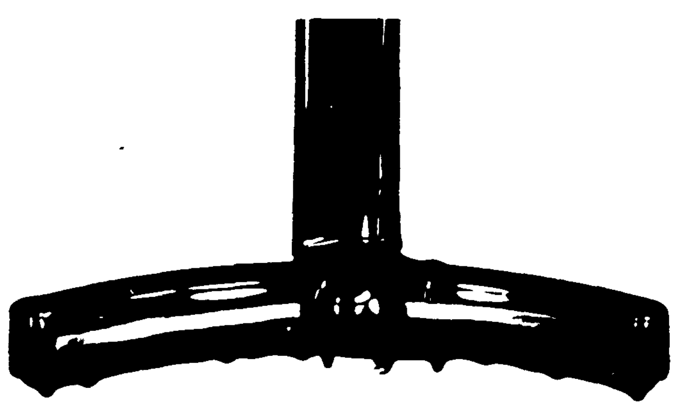
2. Vapor blast with silicon carbide (wet) and with aluminum oxide (wet)
3. Cold water rinse and keep under water while masking and until placed in plating tank with current on
4. Plate at 6.5 to 7 amp for 24 hr in GMR Iron Plating Solution using two circular type anodes as shown in Figure 17
5. Solution agitate by rotating mask and gear assembly and by impeller solution agitation
6. Unmask
7. Water rinse and dry

HARD SURFACE COAT BONDING

The system of bonding the hard surface coating to the titanium base consisted of the application of a strike of electroless nickel (Nichem treatment) to the bare titanium prior to plating. The bond generated had sufficient strength to withstand low temperature case hardening treatments, but with the inclusion of higher temperature (i.e., 1550°F or above and quenching), loss-of-bond failures became predominate. The condition was particularly apparent on the first full-scale set of Tribometer and three-ball-and-cone specimens manufactured. Bond failures were observed on over half the Tribometer and three-ball-cone specimens. The failures occurred principally during the carbonitriding cycle or the quench operation.

Titanium samples incorporating a Nichem strike and iron-nickel surface coating were subjected to a vacuum at 1675°F temperature for four hours. Examination of the bond interface revealed the diffusion zone to be narrow with the Nichem apparently acting as a barrier to deep diffusion.

Microhardness examination revealed a considerable reduction in hardness of the zone as compared with the base titanium. It was recognized that an improvement might be obtained by increasing the depth of diffusion penetration since an increase in both hardness and strength



7326-18

Figure 17. Shielded plating anode.

could be derived by an extended or broadened diffusion zone. The decision was made to attempt plating and diffusion of iron-nickel on chemically clean Ti 6Al-2Sn-4Zr-6Mo alloy.

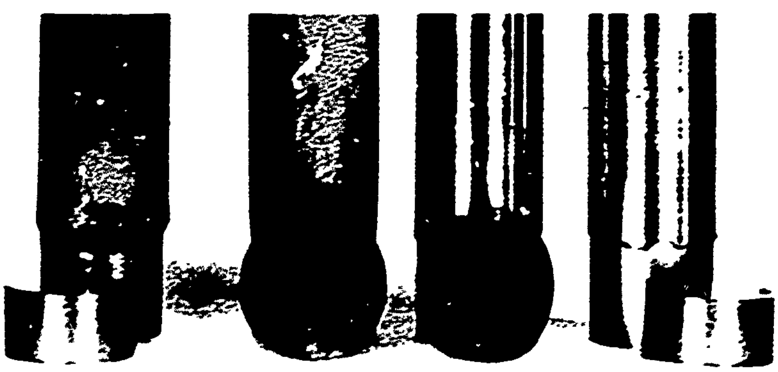
Round Ti 6Al-2Sn-4Zr-6Mo specimens were chemically cleaned and plated with iron-nickel. The specimens were then loaded across their OD by a C-clamp device resulting in an unloaded surface 180 degrees to the clamp. The specimens were then subjected to 1675°F for four hours in a vacuum furnace. The temperature selected represented the highest safe temperature below the beta transus of the alloy.

Examination of the specimens revealed a smooth, continuous adherent coating with the following conditions.

- Diffusion depth was increased beyond the plating interface.
- No appreciable difference could be found between areas subjected to clamping and adjacent areas left in the free state.
- Both diffusion into the titanium and back diffusion into the iron-nickel was accomplished.
- Diffusion zone microhardness was in the Rc35 range which was a considerable improvement over the previous diffusion zone hardness of Rc 25-28.

Optimization of the diffusion process was attempted in order to expand the information concerning the effects of time and temperature on the basic diffusion process.

Test specimens of Ti 6Al-2Sn-4Zr-6Mo bar stock were manufactured for both iron and iron-nickel coating as shown in Figure 18.



7326-19

Figure 18. Plated titanium diffusion test specimens.

These specimens were evaluated for both iron and iron-nickel coatings for the following temperatures and times:

Temperature (°F)	Time (hr)
1700	1, 2
1675	1, 3, 6
1600	1, 3, 6
1500	1, 3, 6
1300	1, 3, 6

The degree of diffusion is directly related to both time and temperature. The iron-nickel diffusion progresses at a slightly higher rate than the iron alloy. The degree of diffusion for each of the investigated times and temperatures are shown in Table II and the titanium tensile properties are shown in Table III.

The optimum diffusion cycle was selected as 1600°F/3 hours. Photomacrographs of the diffusion zone of both iron and iron-nickel coatings are shown in Figure 19.

Cross diffusion between the titanium and iron is evident at the interface. Lesser degrees of migration are seen to occur for the Ti 6Al-2Sn-4Zr-6Mo alloying elements aluminum, tin, zirconium and molybdenum. This generates what is principally a titanium-iron rich interface.

Table II.

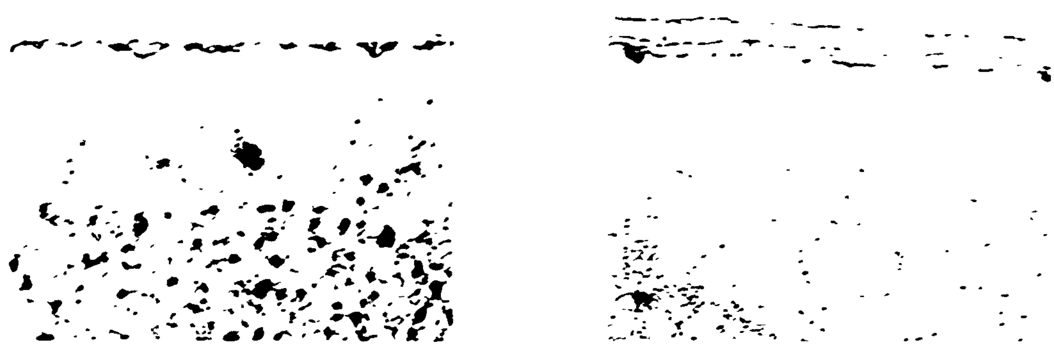
Diffusion depth, inches, of iron and iron-nickel in Ti 6Al-2Sn-4Zr-6Mo.

Coating	Temperature (°F)	Time (hr) 1	3	6
		Diffusion depth (inches)		
Iron	1700	0.002	---	---
	1675	0.002	0.0025	0.0035
	1600	0.001	0.002	0.003
	1500	0.0005	0.001	0.002
	1300	Nil	Nil	0.0005
Iron-nickel	1700	0.002	---	---
	1675	0.002	0.003	0.004
	1600	0.001	0.0025	0.003
	1500	0.0005	0.001	0.002
	1300	Nil	Nil	0.0005

Table III.

Tensile properties after vacuum diffusion.

Temperature, °F	Vacuum diffusion-slow cool time (hr) 1	2	3	4	5
1700					
Ultimate strength, ksi	162.7	167.2	---	---	---
Yield strength, ksi	151.2	153.2	---	---	---
Elongation, %	16.4	15.6	---	---	---
1675					
Ultimate strength, ksi	162.6	---	164.0	166.1	163.0
Yield strength, ksi	150.1	---	151.2	153.6	151.7
Elongation, %	18.8	---	17.4	16.6	18.0
1600					
Ultimate strength, ksi	159.4	---	159.7	---	161.4
Yield strength, ksi	151.0	---	149.1	---	152.3
Elongation, %	15.8	---	16.6	---	17.0
1500					
Ultimate strength, ksi	159.3	---	157.9	---	156.5
Yield strength, ksi	152.0	---	151.8	---	149.7
Elongation, %	16.8	---	15.5	---	12.8
1300					
Ultimate strength, ksi	176.5	---	170.5	---	169.4
Yield strength, ksi	168.1	---	162.0	---	157.5
Elongation, %	15.3	---	13.1	---	15.0



Fe 500X

Fe-Ni 500X

7326-20

Figure 19. Vacuum diffusion zone.

the total diffusion zone of 0.002-0.003 inches. In the case of the iron nickel alloy, the diffusion products are quite similar to the iron but includes a nickel phase at the interface. Electron probe analyses of both systems are shown in Figure 20 and Figure 21.

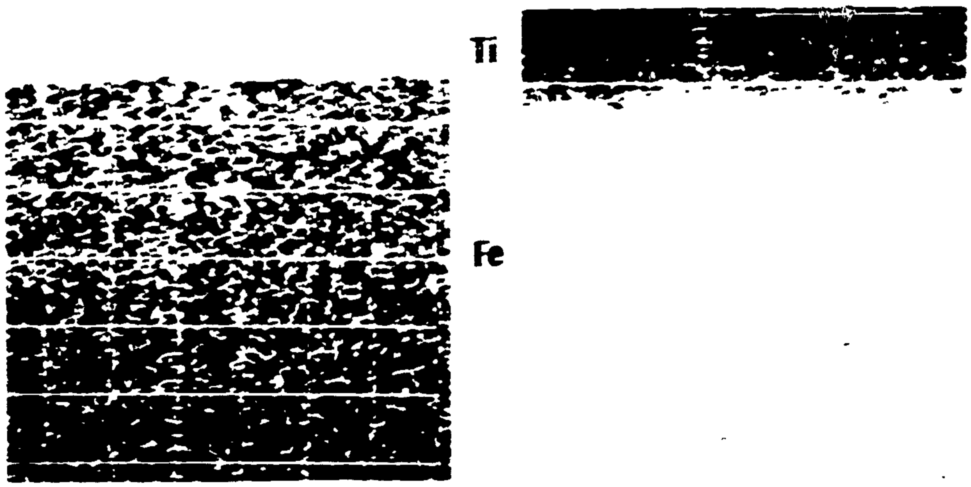


Figure 20. Electron microprobe study of iron coating and titanium.

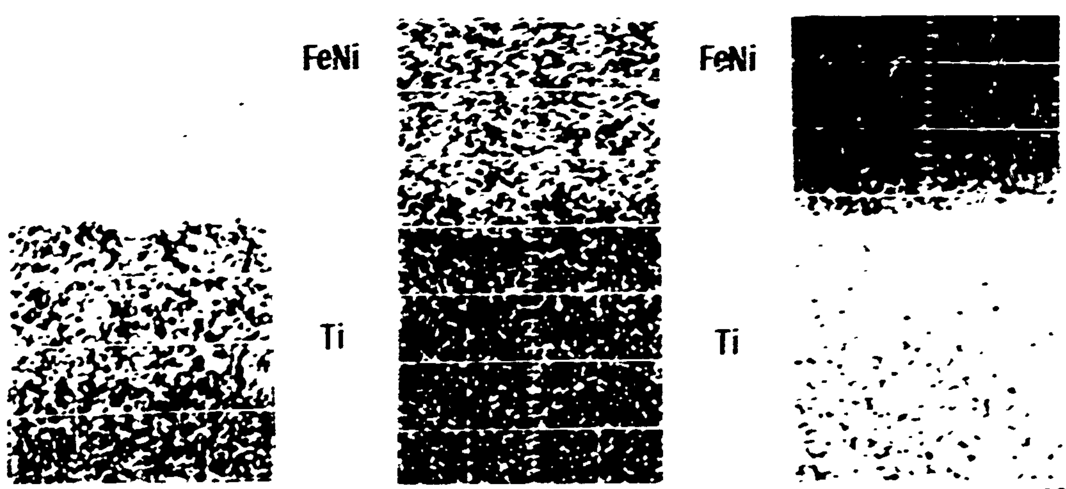


Figure 21. Electron microprobe study of iron-nickel coating and titanium.

HEAT TREATMENT

The objective of the heat treatment process was to achieve R_{15N} 88 minimum surface hardness with adequate depth to support the surface contact stresses and to resist gear tooth surface scoring. The titanium core hardness objective was established at Rc 34 min.

The normally GM Nichem plating process of electroless nickel was used for applying coating thicknesses of up to 24 mils to test specimens. Bonding to the titanium alloy was accomplished by a vacuum heat treatment at 1000°F, followed by a slow cool to room temperature. This procedure proved adequate for the Tribometer and three-ball-and-cone test specimens and resulted in surface hardnesses of Rc 55 to Rc 58 after final grinding.

Identically processed test gear tooth surfaces developed thermal cracks during the postdiffusion cooling or during subsequent final grinding operations.

The use of glass bead peening was implemented to induce compressive surface stresses and thereby reduce the cracking tendency of the Nichem plate. Glass bead peening was used subsequent to the elevated temperature diffusion cycle (1000°F) and subsequent to each grind operation. Although glass bead peening measurably reduced the cracking tendency, the condition could not be eliminated. Because of this condition, further heavy Nichem plate development on gears was suspended. Furthermore, in the initial efforts to bond iron and iron-nickel electrodeposits to the titanium alloy test specimens, an electroless nickel coating 0.1 to 0.2 mil thick was used. The thin Nichem coatings, processed and vacuum heat treated (as previously described) were lightly fine grit wet blasted and electrochemically activated prior to immersion in the iron and iron-nickel plating solutions. The system worked well until the higher temperature heat treatments and rapid quenches were used. Then it was learned that the diffused Nichem would not withstand the thermal shocks.

Earlier work by GM Research Laboratories had determined favorable processes for the hardening of iron deposits by suitable heat treatment. Deposits of iron-nickel having good hardenability were plated on the regular sections of the Tribometer and three-ball-and-cone test specimens. The typical irregular sections of gear teeth resulted in rich deposits of nickel to be deposited on the gear tooth root areas. Although Phase I gears were processed with iron-nickel plating, it was found that the nickel rich areas did not respond favorably to the heat treatment process.

Phase II and III gears were iron plated, therefore, efforts were made to provide optimum heat treatment for the iron plated titanium combination. A review of the heat processes follows.

Nitride Process

Attempts to harden the iron plate by nitriding were unsuccessful. Nitriding was attempted at 900 to 1100°F and with various atmosphere changes, but sufficient surface hardness was not accomplished.

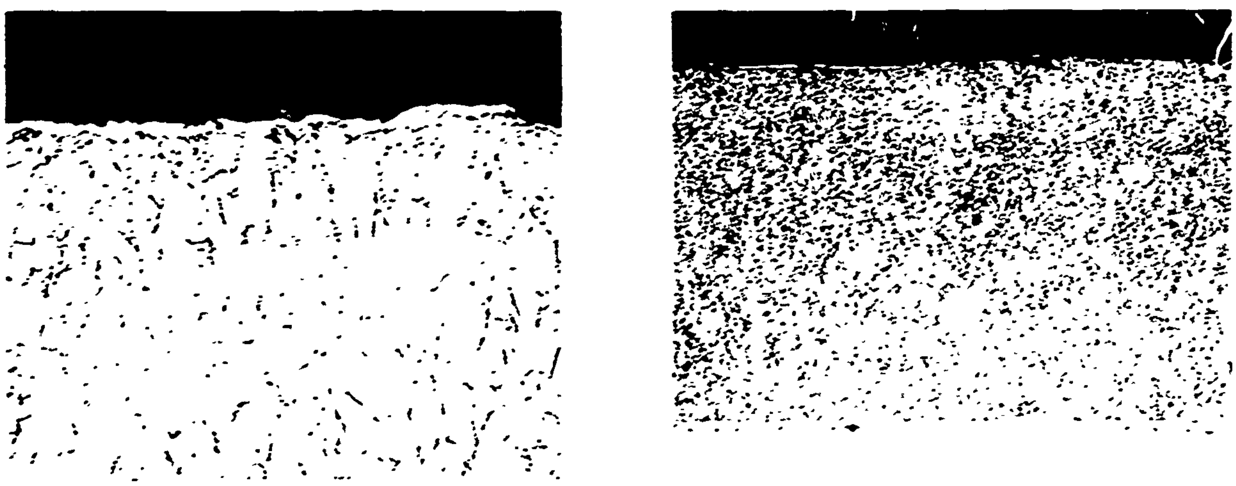
The purpose of the low temperature hardening was to optimize case characteristics in a range which would also provide the maximum core strength capabilities for the titanium substrate. In an attempt to accomplish the case hardening and retain the titanium properties, a second nitriding method was used—the Lindburg Tufftride salt bath process. Although this process provided some improvement in case hardness, the increase proved insufficient for the design case characteristics of the test gears. Micrographs of the Tufftride process are shown in Figure 22.

Carburizing Process

The necessary reduction in heat treatment temperature to retain the major portion of the core strength eliminated carburization as an optimum candidate process. Carburizing provides favorable case structure and hardness after processing at temperatures in excess of 1600°F. The core titanium would not tolerate this processing without an additional heat treat step which would substantially reduce case hardness (i.e., carburized iron complex) and, therefore, was incompatible with the total system requirements.

Carbonitriding Process

From the beginning, the carbonitride process provided substantial improvement in the hardness of iron plate. Initial carbonitriding was accomplished at 1650°F. The use of this temperature plus a quench provided optimum case hardness of Rc 55 or higher. The 1650°F temperature, however, proved incompatible with the titanium base alloy; strength properties of the titanium were drastically reduced. Reduction of the temperature to 1550°F proved to be more compatible



Mgn: 500X Iron

Mgn: 100X Iron

7326-23

Figure 22. Iron coating structures with Tufftride heat treatment.

with the titanium and still provided the necessary hardness in the case. Following an oil quench and tempering, the iron specimens were Rc 55 to 57 (microhardness). To establish complete heat treatment parameters for both the iron plated case and the titanium alloy core, the following carbonitriding heat cycles were evaluated with results as shown in Table IV.

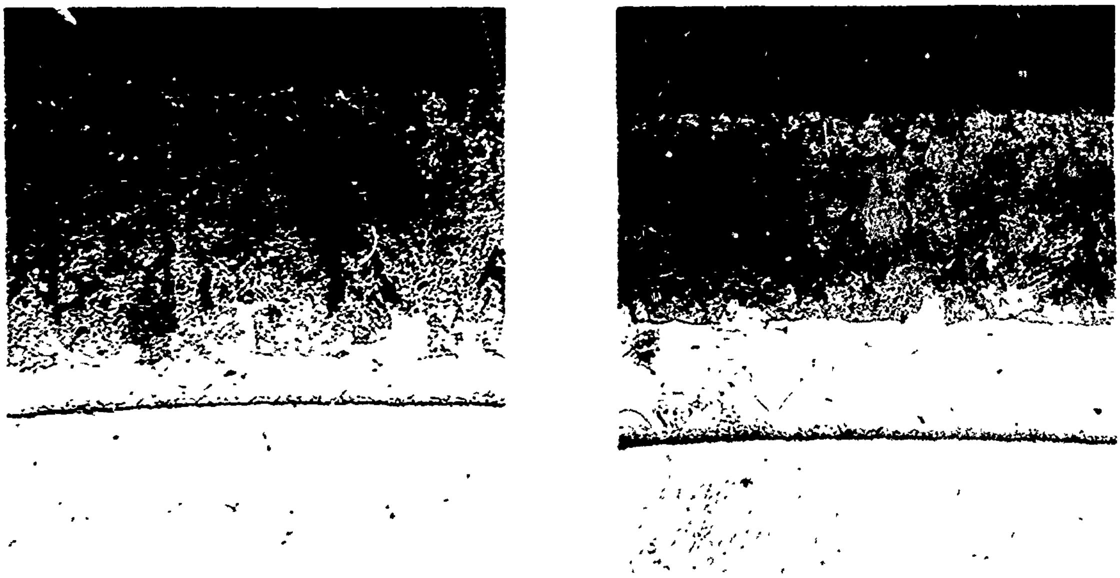
The 1550°F/2.25 hr cycle was selected to achieve hardening of the complete iron plate without producing excessive carbon at the iron-titanium interface. Typical microsections are shown in Figure 23.

The finalized carbonitride process is as follows:

- Preheat gears to 500°F
- Carbonitride at 1550°F/2.25 hr:
  - 35 min—1.5 ft^3 propane gas
    2.0 ft^3 ammonia

Table IV.
Carbonitride surface hardness—depth.

Temperature (°F)	Time (hr)	Surface hardness (R_{15N})	Depth (in.)
1750	6	89.0	---
	4	---	---
1700	6	---	---
	4	89.0	---
1650	6	90.5	---
	4	90.5	---
1600	6	90.5	---
	4	91.0	---
1550	6	88.5	---
	4	90.0	---
	3	91.0	0.017
	2.75	91.0	0.016
	2.5	91.0	0.016
1550	2.25	91.0	0.015
	2.0	89.0	0.010
	1.5	89.0	0.0085
	0.75	88.0	0.007
1500	6	88.5	---
	4	91.5	---



1.5 hr　　Mgn 100X　　2.0 hr　　7326-24

Figure 23. Typical carbonitride of iron on titanium.

  - 90 min—1.0 ft^3 propane gas
    2.0 ft^3 ammonia
  - 10 min—generator gas
- Oil quench at 350°F
- Temper at 350°F/2 hr
- Air-cool to room temperature
- Temper at 350°F/2 hr

This process produces the gradient shown in Figure 24.

Temper Process

The effect of temper on the case hardness of iron and iron-nickel is shown in Tables V through IX. The effect on the core properties is shown in Tables X and XI.

The finalized process used on the final gear sets was the 2.0-2.25 hr cycle at 1550°F temperature followed by two 350°F/2 hr temper cycles. The final properties are shown in Table XII.

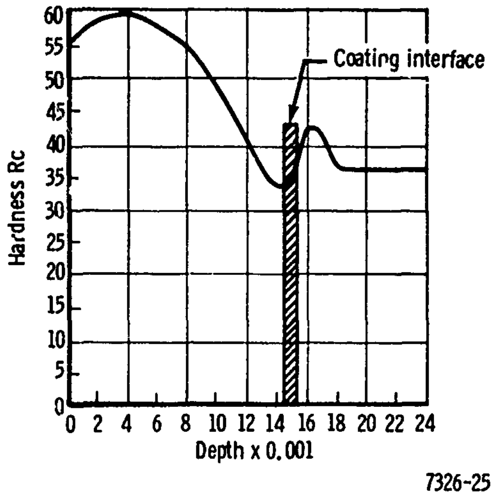


Figure 24. Heat treatment hardness gradient.

Table V.

Effects of low temperature treatment on surface hardness (R_{15N}).

Carbonitride cycle		Oil quench + 350°F/1 hr temper		Low temp—100°F/1 hr plus second 350°F/1 hr temper	
Temperature (°F)	Time (hr)	Fe	Fe+Ni	Fe	Fe+Ni
1700	6	89	83—84	92—93	91—91.5
	4	89	81—83	92—93	90—90.5
1650	6	90—91	87—88	92—92.5	90—91
	4	90—91	83.5—84	92	90—91
1600	6	90—91	87—88	92—93	91.5—92
	4	90—92	85—86	92—94	90.5—91
1550	6	88—89	89	90—91	90
	4	90	88.5—89	91—93	90.5—91.5
1500	6	88—88.5	87	90	89.5—90
	4	91—92	86.5—87	91—92	90—91

Table VI.

R_{15N} hardness values of specimens given final high-temperature temper treatment of 450°F.

Carbonitride cycle			Temper time (hr)				
Temperature (°F)	Time (hr)	Plating	2	4	8	12	16
			Hardness				
1700	6	Fe	92	91	91.5	91	91
1700	4	Fe	92	92	91	91	91
1700	6	Fe-Ni	90.5	90.5	90	90.5	90
1700	4	Fe-Ni	89.5	89.5	90.5	89	90.5
1650	6	Fe	91	91	91.5	90.5	90
1650	4	Fe	92	91.5	90	90	90.5
1650	6	Fe-Ni	90.5	90	90	89.5	89.5
1650	4	Fe-Ni	90	89.5	89.5	89	89
1600	6	Fe	91	91.5	90	90.5	90.5
1600	4	Fe	92	91.5	91	91	90.5
1600	6	Fe-Ni	90.5	89.5	89.5	89.5	89
1600	4	Fe-Ni	89	89.5	89.5	89.5	90.5
1550	6	Fe	89.5	89.5	89.5	89.5	89.5
1550	4	Fe	91	90.5	90.5	89.5	90.5
1550	6	Fe-Ni	90	89.5	89.5	89	89.5
1550	4	Fe-Ni	89.5	89.5	89.5	89	89.5
1500	6	Fe	90.5	89.5	89.5	89.5	89.5
1500	4	Fe	91	92	90.5	90.5	90.5
1500	6	Fe-Ni	88.5	88.5	87	89	88.5
1500	4	Fe-Ni	90	89.5	88	89	89.5

Note: Heat treatment prior to final temper treatment.
Diffuse 1600°F/3 hr + carbonitride cycle as indicated + temper 350°F/1 hr + -100°F/1 hr +350°F/1 hr.

Table VII.

R_{15N} hardness values of specimens given final high-temperature temper treatment of 550°F.

Carbonitride cycle			Temper time (hr)		
Temperature (°F)	Time (hr)	Plating	2	4	8
			Hardness		
1700	6	Fe	89	88.5	88.5
1700	4	Fe	88.5	88.5	89
1700	6	Fe-Ni	88	88	87.5
1700	4	Fe-Ni	88	87	87.5
1650	6	Fe	89.5	88	88.5
1650	4	Fe	89.5	88.5	88.5
1650	6	Fe-Ni	88.5	88	86.5
1650	4	Fe-Ni	87.5	88	86.5
1600	6	Fe	89	89	88.5
1600	4	Fe	89.5	89	88
1600	6	Fe-Ni	87.5	88	87.5
1600	4	Fe-Ni	88	88	87.5
1550	6	Fe	88.5	88	87.5
1550	4	Fe	89	89	88
1550	6	Fe-Ni	88	87.5	87
1550	4	Fe-Ni	88.5	88	87.5
1500	6	Fe	87.5	87.5	88
1500	4	Fe	89.5	89.5	89
1500	6	Fe-Ni	86.5	86.5	85.5
1500	4	Fe-Ni	87.5	86.5	86.5

Note: Heat treatment prior to final temper treatment.
Diffuse 1600°F/3 hr + carbonitride cycle as indicated + complex temper 350°F/1 hr + -100°F/1 hr + 350°F/1 hr.

Table VIII.

R_{15N} hardness values of specimens given final high-temperature temper treatment of 650°F, 750°F, and 900°F.

Carbonitride cycle			Final temper		
Temperature (°F)	Time (hr)	Plating	650°F 2 hr	750°F 2 hr	900°F 1 hr
1700	6	Fe	86.5	86.5	79.5
1700	4	Fe	87	86.5	79
1700	6	Fe-Ni	85.5	85	80
1700	4	Fe-Ni	85	85	80.5
1650	6	Fe	86.5	86.5	79.5
1650	4	Fe	87	86	80
1650	6	Fe-Ni	85	85.5	80
1650	4	Fe-Ni	84.5	84	79
1600	6	Fe	86	86	79.5
1600	4	Fe	86.5	86	80
1600	6	Fe-Ni	85	85	77.5
1600	4	Fe-Ni	86	85.5	79.5
1550	6	Fe	85.5	84	78
1550	4	Fe	86.5	86.5	78
1550	6	Fe-Ni	85	84.5	79
1550	4	Fe-Ni	85.5	84	77.5
1550	6	Fe	85	83.5	77
1500	4	Fe	86.5	85.5	79
1500	6	Fe-Ni	83.5	83	78
1500	4	Fe-Ni	84.5	83.5	78

Note: Heat treatment prior to final temper treatment.
Diffuser 1600°F/3 hr + carbonitride cycle as indicated + complex temper 350°F/1 hr + -100°F/1 hr + 350°F/1 hr.

Table IX.

R_{15N} hardness values of specimens given final high-temperature temper treatment of 500°F.

Carbonitride cycle Temperature (°F)	Time (hr)	Plating	Temper time (hr) 4	12	18
			Hardness		
1700	6	Fe	90	89.5	88.5
1700	4	Fe	91	90	89
1700	6	Fe-Ni	89.5	88.5	88
1700	4	Fe-Ni	89.5	88.5	87.5
1650	6	Fe	90	89.5	88.5
1650	4	Fe	90.5	89.5	88
1650	6	Fe-Ni	89.5	88.5	88
1650	4	Fe-Ni	88.5	88	88
1600	6	Fe	90	90	89
1600	4	Fe	90.5	---	---
1600	6	Fe-Ni	89.5	88.5	87.5
1600	4	Fe-Ni	---	89	88.5

Note: Heat treatment prior to final temper treatment. Diffuser 1600°F/3 hr + carbonitride cycle as indicated + temper 350°F/1 hr + -100°F/1 hr + 350°F/1 hr.

Table X.

Tensile properties after simulated 600°F carbonitride and 350 to 950°F temper.

Only the final temper time and temperatures being varied as indicated.

Processing Temperature (°F)	Time (hr)
1600	3
Slow cool	
1600	5 (Simulate carbonitride)
Oil quench	
350	1
-100	1
350	1
Final temper as indicated	

Temperature (°F)	Time (hr)	Ultimate strength (ksi)	Yield strength (ksi)	Elongation (%)	Reduction of area (%)
950	2	203.2	184.1	6.5	11.6
750	2	193.8	169.5	11.9	24.8
650	2	168.4	154.8	11.8	25.0
550	12	171.5	163.1	11.0	23.2
550	8	162.6	158.4	14.7	30.0
550	4	151.9	146.7	17.0	30.4
550	2	152.9	144.5	14.6	21.9
500	18	159.5	157.8	16.0	38.5
500	12*	157.3	153.6	16.3	30.2
500	8	156.6	154.8	13.5	23.3
500	4	160.4	154.8	14.0	27.0
500	2	150.1	142.5	19.4	23.2
450	24	151.9	148.9	16.8	33.6
450	18	150.9	148.8	19.7	35.6
450	2	149.3	141.9	16.0	21.7
350	2**	149.9	138.0	17.6	36.2

Notes: Hardness values of specimens below the line meet or exceed $R_{15N}88$ minimum value for iron cases.

*Optimum cycle for titanium core strength and iron case hard.

**No low temperature treatment (-100°F).

Table XI.

Tensile properties after simulated 1550°F carbocitride and 350 to 950°F temper.

Only the final temper time and temperatures being varied as indicated.	Processing	
	Temperature (°F)	Time (hr)
	1550	3
	Slow cool	
	1550	5 (Simulate carbocitride)
	Oil quench	
	350	1
	-100	1
	350	1
	Final temper as indicated	

Temperature (°F)	Time (hr)	Ultimate strength (ksi)	Yield strength (ksi)	Elongation (%)	Reduction of area (%)
950	2	193.9	167.7	7.7	8.7
750	2	162.9	147.9	17.7	32.6
650	2	149.3	142.7	17.4	28.6
550	8	149.9	143.2	22.1	29.4
550	2	149.3	142.6	16.3	28.2
450	8	149.5	145.3	17.1	37.1
450	2	150.3	145.6	15.7	30.3
350	2*	150.3	144.1	18.5	40.0

Note: Hardness values of specimens below the line meet or exceed the $R_{15N}88$ minimum value for iron cases. Iron-nickel values are 1-2 points less.

*No low temperature treatment (-100°F).

SURFACE LUBRICANT COATINGS

Solid surface lubricant coatings offer a means of preventing sliding friction damage during periods of limited lubrication or failure of the primary lubrication system. The solid lubricants are of great importance during the original break-in running of gear assemblies because of their ability to shear internally and to move and accommodate to surface discrepancies. Furthermore, they are very adherent to loaded surfaces and have the capacity to retain oil films which can supply lubrication for appreciable periods of time after failure of an oil supply system.

Table XIII.

Titanium material properties with 2.0—2.25 carbonitride cycle.

Sample No.	Ultimate strength (ksi)	Yield strength (ksi)	Elongation (%)	Reduction of area (%)
1	148.3	141.3	7.8	12.4
2	149.1	141.5	6.1	10.0
3	148.7	140.5	6.7	10.8
4	150.7	146.7	7.9	18.8
5	148.3	151.7	8.7	12.1
6	148.7	141.3	9.8	14.8
7	148.3	142.1	10.1	15.2
8	148.5	145.9	4.8	10.9
Average	149.2	143.6	7.7	13.1

Core hardness (titanium) = Rc37.

The solid surface lubricants chosen for this program had demonstrated capabilities of good prop. ties at ambient and elevated temperatures.

Dow Corning 1-3943 (AFML-41)

This solid surface lubricant is a development of the Air Force Materials Laboratories which has been licensed to Dow-Corning for manufacture and sales. It consists of molybdenum disulfide and antimony trioxide in a resin binder and was spray gun applied. Films of the coating in thicknesses of 0.5 to 1.0 mil were applied to Tribometer, three-ball-and-cone, and Ryder gear test specimens. After spray application, the films were air cured at 350°F temperature for two hours.

Silver + Niobium Telluride $Ag\text{-}NbTe_2$

This solid surface lubricant which is applied electrophoretically is a proprietary development of Detroit Diesel Allison and is the subject of current patent proceedings. The fine particles of silver and niobium telluride are codeposited at room temperature to a thickness of 0.2 to 0.3 mils and require no further treatment.

Teflon + Molybdenum Disulfide (Teflon-MoS_2)

Finely divided particles of Teflon and molybdenum disulfide are electrophoretically codeposited to a thickness of 1.0 to 2.0 mils. This also is a proprietary process of Detroit Diesel Allison and is a subject of current patent proceedings. The coating was tested on Tribometer specimens only. Its property of extruding under pressure and piling up outside the load pattern made it less desirable for the three-ball-and-cone and Ryder gear surfaces.

SECTION III

GEAR DESIGN

The gears were designed to operate on the Ryder gear tester requiring 3.5-in. center distance. Two sets were designed which are designated as Phase I and Phase II and III gears.

PHASE I GEAR DESIGN

Phase I gears were designed for 159,000 psi hertzian contact stress based on steel modulus of elasticity of 30.0×10^6 psi. The equivalent contact stress for titanium is 126,000 psi based on a modulus of 16.5×10^6 psi. The hertzian stress equation used for calculation is

$$S_c = \frac{0.564}{\sqrt{1-\mu}}\left[\frac{W_t \times E}{\sin\phi \times 2 \times \cos\phi \times Fe}\left(\frac{R_G + R_P}{R_G \times R_P}\right)\right]^{1/2}$$

$$W_T = \frac{TQ}{R_P}$$

where:

- μ = Poisson's ratio
- E = Young's modulus of elasticity ... $\times 10$ ... psi
- W_T = tangential load - 667 lb
- ϕ = pressure angle at pitch dia = 25 degrees
- Fe = effective face width = 0.360 in.
- R_G = pitch radius—gear = 1.750 in.
- R_P = pitch radius—pinion = 1.750 in.
- TQ = torque = 1058 lb-in.

The face width of the gears was modified to accommodate the axial travel for the loading mechanism of the Ryder rig, thereby providing full engagement of the narrow gear throughout the operating range of the test schedule.

The tooth thickness of both gears was modified to maintain balanced bending deflection between the narrow and wide gears. The Lewis stress equation used to calculate the bending stress with the load applied at the high point of single tooth contact (HPSTC) is as follows:

$$S_b = \frac{3TQ}{D_V\ F_{min}\ X_{HPSTC}}$$

where:

D_V : vertex of parabola at HPSTC

F_{min} : minimum face width—in.

X_{HPSTC} : X factor at HPSTC

Bending stress geometry is shown in Figure 25.

The total tooth deflection is the sum of the tooth bending deflection based on Weber's equation and the surface deflection based on Hertz equation.

Detailed section of the Phase I finished gears are shown in Figure 26 and Figure 27.

Both gears incorporated full fillet radii and tooth profile modification of 0.0004 inch outboard of the HPSTC. The load schedule and related data for the Phase I gears is shown in Table XIII and Table XIV.

Figure 28 shows the bending and Hertz stresses relative to pounds per inch (PPI) of face width.

Phase II and III Gear Design

The Phase II gears shown in Figures 29 and 30 were designed to produce 185,000 psi Hertz contact stress based on the steel modulus of elasticity of 30.0×10^5 and a Poisson's ratio of 0.30. The 185,000 psi stress is equivalent to 140,000 psi Hertz contact for titanium with a modulus of elasticity of 16.5×10^6 and a Poisson's ratio of 0.35. This stress is developed on an effective face width of 0.250 when operating on the Ryder test rig at 14,000 rpm.

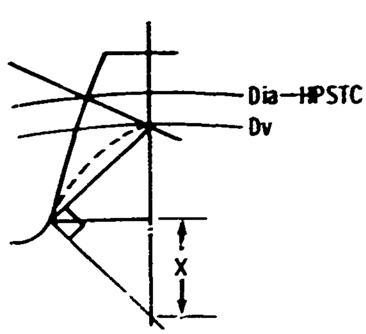


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Figure 25. Bending stress geometry.

Spur Gear Data
10.2857141 pitch 36 teeth
25° pressure angle
Distance over two 0.1728 dia pins = 3.721976 +0.0040 -0.0000
Root dia = 3.263 ± 0.005
Pitch dia = 3.5000
Active profile outside = 3.33307035 dia
Reference
Arc tooth thickness at PD = 0.139416 ±0.001
0.006 to 0.010 backlash with mating gear on standard centers
Base circle dia = 3.17207731

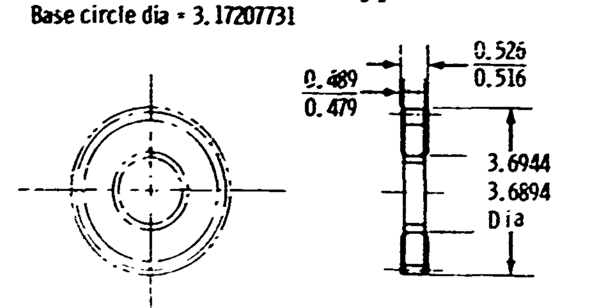

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Figure 26. Phase I wide gear design.

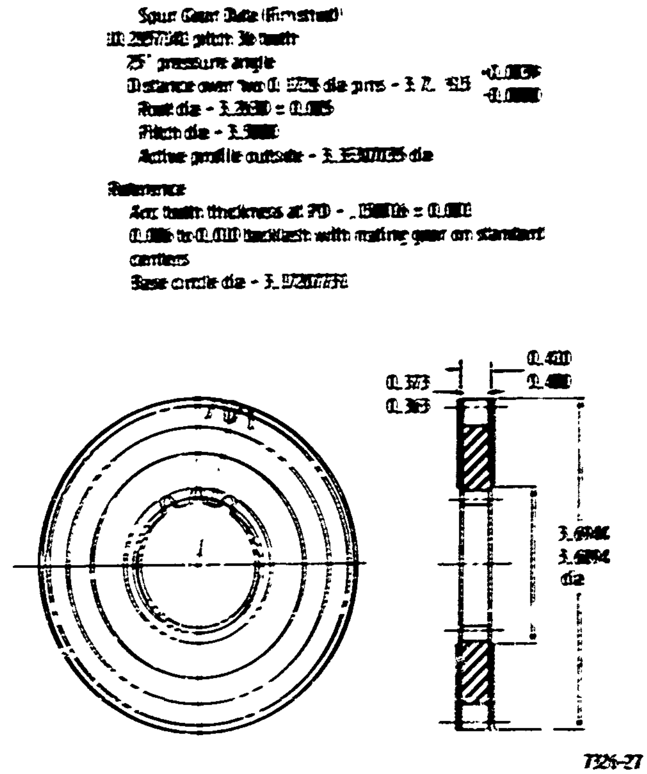


Figure 27. Phase I narrow gear design.

Table XIII.

Phase I test schedule—surface stress.

Test time (hr)	Total cycles (× 10^6)	Torque (lb-in.)	Normal tooth load (lb)	Surface stress at pitch line (psi) (Hz) Titanium*	Steel**
10.0	8.4	470.3	296.5	80,000	105,928
10.0	16.8	530.9	334.7	85,000	112,549
10.0	25.2	595.2	375.3	90,000	119,169
20.0	42.0	663.2	418.1	95,000	125,790
20.0	58.8	734.9	463.3	100,000	132,410
20.0	75.6	810.2	510.8	105,000	139,031
20.0	92.4	889.2	560.6	110,000	145,651
20.0	109.2	971.9	612.8	115,000	152,272
20.0	126.0	1,058.2	667.2	120,000	158,892

*Young's modulus--titanium 16.5 × 10^6; Poisson's ratio-titanium 0.35.

**Young's modulus—steel 30.0 × 10^6; Poisson's ratio-steel 0.30

Table XIV.

Phase I test schedule—bending stress.

Test time (hr)	Bending stress at HPSTC* (psi) Pinion	Bending stress at HPSTC* (psi) Gear	Bending deflection at HPSTC* Total pinion (in.) Titanium
10.0	8,822	8,317	0.00041
10.0	9,959	9,389	0.00046
10.0	11,165	10,526	0.00052
20.0	12,440	11,728	0.00058
20.0	13,784	12,995	0.00064
20.0	15,197	14,327	0.00071
20.0	16,679	15,724	0.00077
20.0	18,230	17,186	0.00085
20.0	19,849	18,713	0.00092

*HPSTC-high point single tooth contact.

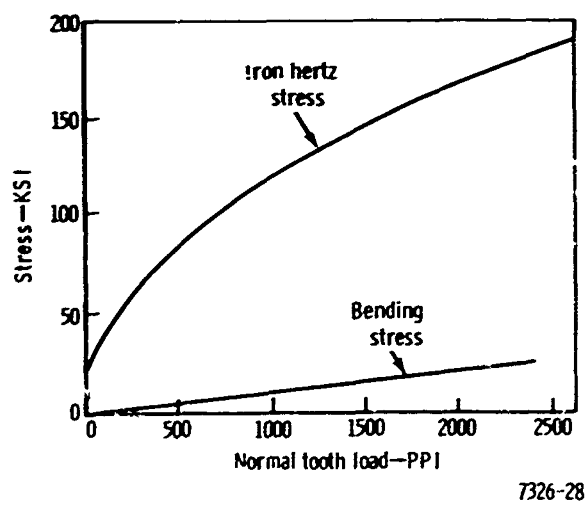


Figure 28. Subsurface stress distribution.

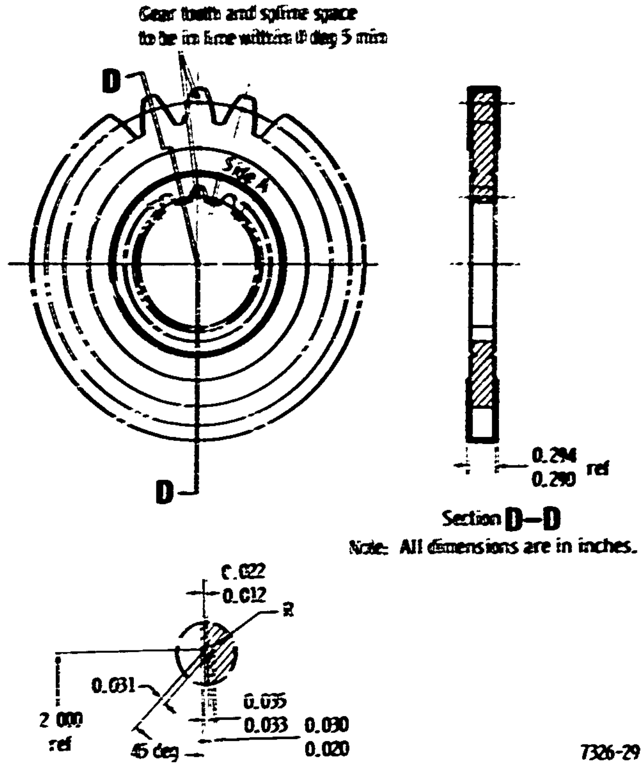


Figure 29. Phase II narrow gear design.

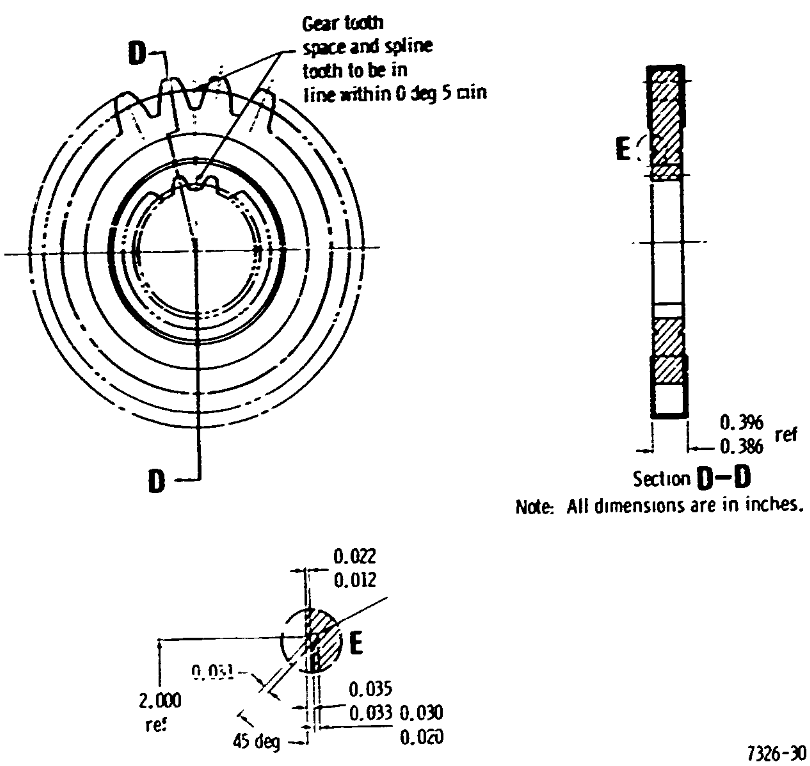


Figure 30. Phase II wide gear design.

To provide a reduced Lewis bending stress of 17,849 psi, 6.0 diametral pitch, 21 teeth, and 25 degrees pressure angle was selected. The minimum profile contact ratio for this selection is 1.362. The selection of this gear tooth geometry reduces the total tooth Hertzian and Weber bending deflection to 0.0009 at the high point of single tooth contact for the maximum load condition to produce the 185,000 psi Hertz stress.

The face width of the gears was modified to accommodate the axial travel for the loading mechanism of the Ryder rig and thereby providing full engagement of the narrow gear throughout the operating range up to the design test objective of 185,000 psi Hertz contact stress.

The load schedule and related data for the Phase II and III gears is shown in Table XV and Table XVI. Complete assessment of the 6.0 diametral pitch gears is made by DDA spur gear computer program and is shown in Appendix I.

Table XV.
Phase II and III test schedule—surface stress.

Test time (hr)	Total cycles ($\times 10^6$)	Torque (lb-in.)	Normal tooth load (lb)	Surface stress at pitch line (psi) Titanium*	Steel**
2	1.68	176.3	111.1	60,000	79,430
2	3.36	239.9	151.3	70,000	92,650
2	5.04	313.4	197.6	80,000	105,910
2	6.72	396.6	250.1	90,000	119,150
2	8.40	489.7	308.7	100,000	132,380
10	16.80	592.5	373.6	110,000	145,640
10	25.20	705.1	444.6	120,000	158,750
10	33.60	827.5	521.8	130,000	172,000
10	42.00	959.7	605.1	140,000	185,000

*16.5×10^6
**30.0×10^6

Table XVI.
Phase II and III test schedule bending stress.

Test time (hr)	Bending stress HPSTC (psi)	Bending deflection HPSTC total pinion (in.)
2	3,279	0.0002
2	4,462	0.0003
2	5,828	0.0004
2	7,377	0.0006
2	9,107	0.0007
10	11,019	0.0008
10	13,114	0.0010
10	15,391	0.0012
10	17,849	0.0014

SECTION IV

GEAR MANUFACTURE

The manufacture of hard coated titanium gears consists of 35 manufacturing operations requiring 24.0 hr set-up time and 30.3 hr manufacturing time for Model Shop fabrication. Manufacturing details are described in the routing sheets shown in Appendix II. Figure 31 shows the gear tooth profile as manufactured.

Process sequence for Phase I, II, and III gears is as follows:

- Hob
- Preplate grind (Phase I and III only)
- Plate (FeNi for Phase I, Fe for Phases II and III)
- Diffusion bond
- Preheat treat grind
- Carbonitride
- Finish grind
- Lube coat

The involute profiles were full form ground using cams manufactured by a numerical control (N/C) system developed at DDA. This grind process ensured plating uniformity of the entire root fillet and involute profile.

Process dimensions are shown in Tables XVII and XVIII.

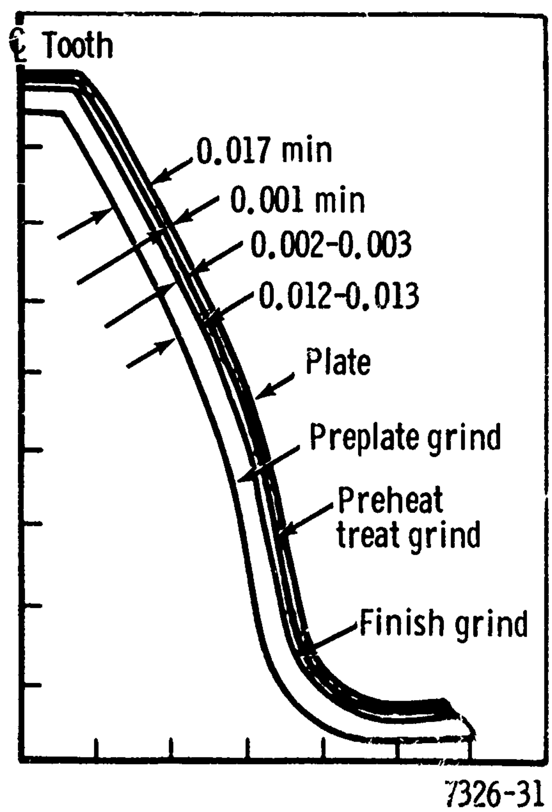


Figure 31. Manufacture of gear tooth profile.

Table XVII.
Phase I, II, and III narrow gear process dimensions (in.).

	Phase	Dimension over pins	Arc tooth thickness	Root dia	Outside dia	Root fillet radius	Face width
	I	3.750±0.002	---	3.250±0.005	3.656±0.005	---	$\frac{0.363}{0.373}$
Hob	II	3.875±0.002	---	$3.110^{+0.000}_{-0.005}$	$3.803^{+0.000}_{-0.005}$	---	$\frac{0.260}{0.270}$
	III	3.875±0.002	---	3.100±0.005	$3.803^{+0.000}_{-0.001}$	---	$\frac{0.266}{0.268}$
Preplate grind	I	$3.704^{+0.004}_{-0.000}$	$\frac{0.130}{0.132}$	3.234±0.005	3.656±0.003	0.048	$\frac{0.363}{0.373}$
	II	$3.843^{+0.006}_{-0.000}$	$\frac{0.238}{0.241}$	$3.0700^{+0.000}_{-0.005}$	$3.803^{+0.000}_{-0.005}$	$\frac{0.075}{0.085}$	$\frac{0.260}{0.270}$
	III	$3.852^{+0.000}_{-0.003}$	$\frac{0.240}{0.242}$	$3.075^{+0.000}_{-0.001}$	$3.808^{+0.000}_{-0.001}$	$\frac{0.079}{0.085}$	$\frac{0.266}{0.268}$
	I	0.025 minimum					
Plate	II	0.020 minimum					
	III	0.017 minimum					
Preheat treat grind	I	$3.774^{+0.005}_{-0.000}$	$\frac{0.165}{0.167}$	3.273±0.005	$3.694^{+0.000}_{-0.005}$	0.032	$\frac{0.405}{0.415}$
	II	$3.920^{+0.006}_{-0.000}$	$\frac{0.278}{0.281}$	$3.110^{+0.000}_{-0.005}$	$3.843^{+0.000}_{-0.005}$	$\frac{0.058}{0.068}$	$\frac{0.300}{0.310}$
	III	$3.915^{+0.000}_{-0.008}$	$\frac{0.277}{0.275}$	$3.106^{+0.000}_{-0.001}$	$3.839^{+0.000}_{-0.001}$	$\frac{0.064}{0.070}$	$\frac{0.294}{0.300}$
Final grind	I	$3.759^{+0.004}_{-0.000}$	$\frac{0.157}{0.158}$	3.263±0.005	$3.694^{+0.000}_{-0.005}$	0.034	$\frac{0.400}{0.410}$
	II	$3.902^{+0.006}_{-0.000}$	$\frac{0.268}{0.271}$	$3.100^{+0.000}_{-0.005}$	$3.833^{+0.000}_{-0.005}$	$\frac{0.062}{0.072}$	$\frac{0.290}{0.300}$
	III	$3.904^{+0.000}_{-0.003}$	$\frac{0.268}{0.269}$	$3.100^{+0.000}_{-0.001}$	$3.833^{+0.000}_{-0.001}$	$\frac{0.067}{0.073}$	$\frac{0.290}{0.294}$

Table XVIII.

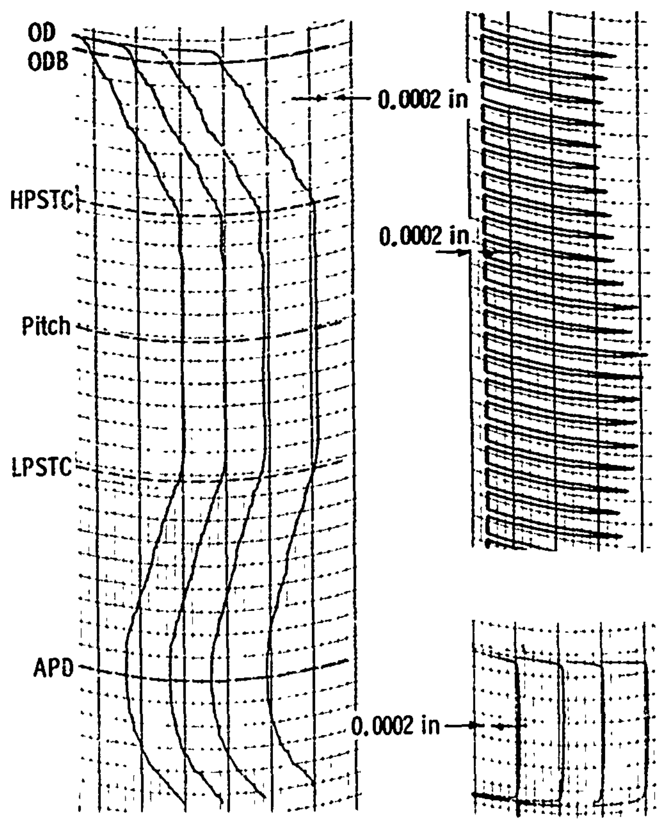
Phase I, II, and III wide gear process dimensions (in.).

	Phase	Dimension over pins	Arc tooth thickness	Root dia	Outside dia	Root fillet radius	Face width
Hob	I	3.680±0.005	---	3.250±0.005	3.656±0.005	---	$\frac{0.379}{0.389}$
	II	3.875±0.002	---	3.110±0.005	$3.803^{+0.000}_{-0.005}$	---	$\frac{0.356}{0.366}$
	III	3.875±0.002	---	3.100±0.005	$3.803^{+0.000}_{-0.001}$	---	$\frac{0.370}{0.372}$
Preplate grind	I	$3.66558^{+0.004}_{-0.000}$	$\frac{0.111}{0.113}$	3.234±0.005	3.656±0.005	0.048	$\frac{0.479}{0.489}$
	II	$3.78242^{+0.006}_{-0.000}$	$\frac{0.208}{0.211}$	$3.070^{+0.000}_{-0.005}$	$3.303^{+0.000}_{-0.005}$	$\frac{0.093}{0.103}$	$\frac{0.356}{0.366}$
	III	$3.79088^{+0.000}_{-0.003}$	$\frac{0.210}{0.212}$	$3.075^{+0.000}_{-0.001}$	$3.808^{+0.000}_{-0.001}$	$\frac{0.097}{0.103}$	$\frac{0.370}{0.372}$
Plate	I	0.025 minimum					
	II	0.020 minimum					
	III	0.017 minimum					
Preheat treat grind	I	$3.738^{+0.004}_{-0.000}$	$\frac{0.146}{0.148}$	3.273±0.005	$3.694^{+0.000}_{-0.005}$	0.032	$\frac{0.521}{0.531}$
	II	$3.863^{+0.006}_{-0.000}$	$\frac{0.248}{0.251}$	$3.110^{+0.000}_{-0.005}$	$3.843^{+0.000}_{-0.005}$	$\frac{0.075}{0.085}$	$\frac{0.396}{0.406}$
	III	$3.858^{+0.000}_{-0.003}$	$\frac{0.243}{0.249}$	$3.105^{+0.000}_{-0.001}$	$3.833^{+0.000}_{-0.001}$	$\frac{0.082}{0.088}$	$\frac{0.400}{0.406}$
Final grind	I	$3.722^{+0.004}_{-0.000}$	$\frac{0.140}{0.138}$	3.263±0.005	$3.694^{+0.000}_{-0.005}$	0.03[illegible]	$\frac{0.516}{0.526}$
	II	$3.844^{+0.006}_{-0.000}$	$\frac{0.238}{0.241}$	$3.100^{+0.000}_{-0.005}$	$3.833^{+0.000}_{-0.005}$	$\frac{0.086}{0.090}$	$\frac{0.386}{0.396}$
	III	$3.847^{+0.000}_{-0.003}$	$\frac{0.238}{0.239}$	$3.100^{+0.000}_{-0.001}$	$3.833^{+0.000}_{-0.001}$	$\frac{0.084}{0.090}$	$\frac{0.396}{0.400}$

Typical inspection charts of manufacturing control are shown in Figure 32.

Manufacture of iron coated titanium gears revealed a strong tendency for the coating system to crack during processing. A number 13 BT glass bead peen at 40 psig was implemented to provide compressive stresses superimposed over any residual tensile processing stresses. This procedure also tends to unify stress distribution across the gear surface. In addition to eliminating surface cracking the peen operation improved the surface finish to 16 rms. Further improvement in the surface finish was accomplished by the Hone operation which reduced the finish to approximately 4 rms.

Electron probe and micrographic analysis of gears with defective plate revealed residual silicone carbide particles at the iron and titanium interface. These particles were suspected to have come from the blasting or cleaning operation prior to plating. Several tests were made and aluminum oxide was selected as a replacement media. Subsequent examination revealed very little aluminum oxide adhered to the gears and what was present appeared to disperse



Typical profile chart—
narrow and wide gears

Typical tooth spacing chart

OD - outer diameter
ODB - outer diameter break
HPSTC - high point single tooth contact
LPSTC - low point single tooth contact
APD - active profile diameter

7326-32

Figure 32. Typical gear inspection charts.

during the vacuum diffusion treatment. The silicon carbide was no longer in evidence and the percentage of defective titanium to iron diffusion bonded gears dropped to near zero.

Postheat treatment cracking was primarily caused by grind induced stresses which were corrected by modification to low stress grinding procedures consisting of reduced grinding wheel speeds, softer grade grinding wheels, and reduced infeed rates. This process was followed by glass bead peening of the part.

Finished gears are shown in Figures 33 and 34.

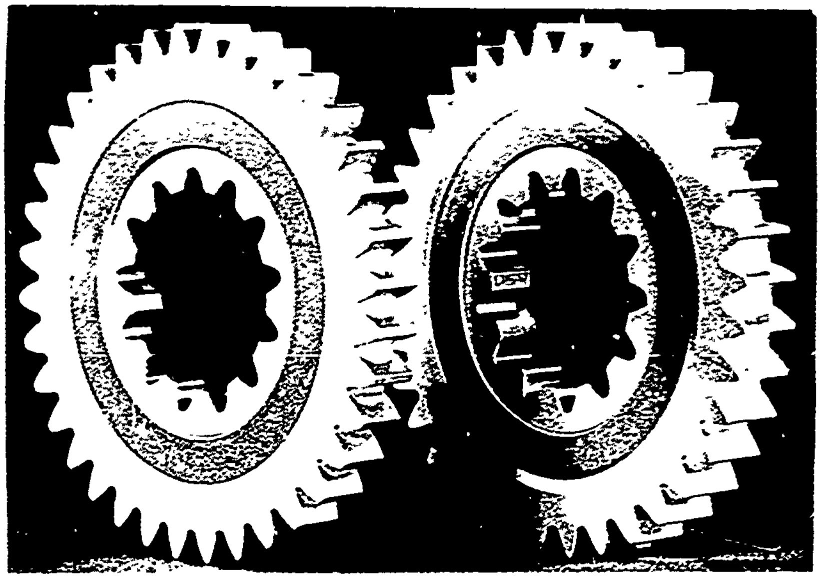


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Figure 33. Phase I finished gear set.

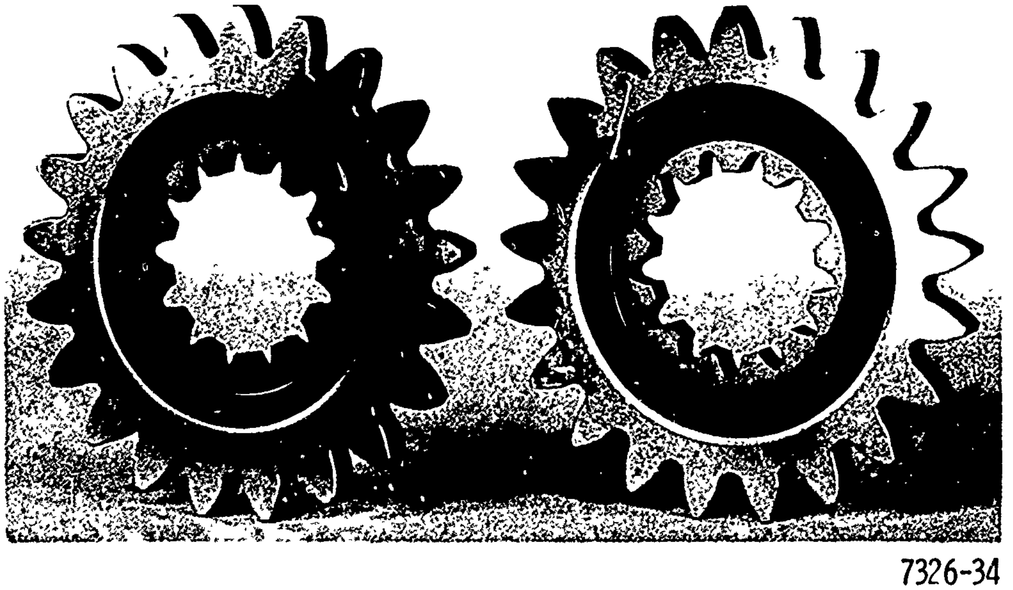

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Figure 34. Phase III finished gear set.

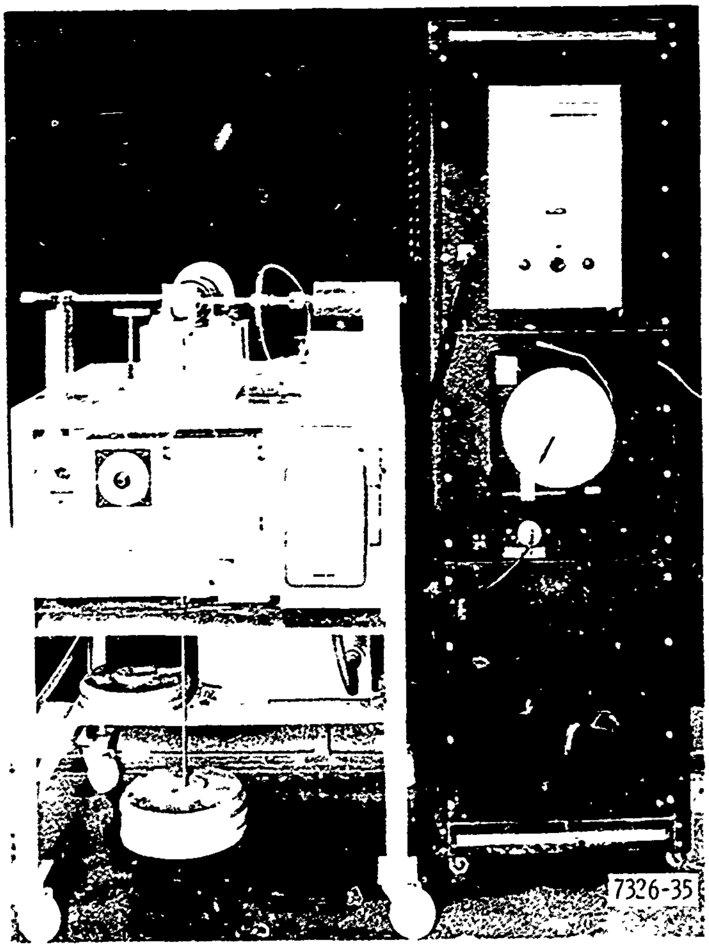
SECTION V

TESTING/ANALYSIS

TRIBOMETER TESTS

The Tribometer, designed and constructed by DDA, permits the determination of static coefficient of friction as well as the profile of the wear surfaces. This rig consists of a loading system, stationary specimen holder, oscillating test shaft, and recording instrumentation. Figure 35 is a front view of the test rig with its test parameters.

Tribometer rotating and fixed test specimens were fabricated from Ti 6Al-2Sn-4Zr-6Mo, plated and finished as shown in Figure 36 and Figure 37 to maintain 0.015 inch plate thickness with Rc 55-58 surface hardness.



Temperature—ambient
Applied load (static)—100 lb
Angular motion—60 degrees
Oscillation frequency—16 Hz
Test time—1000 cycles

Figure 35. Tribometer test rig and test parameters.

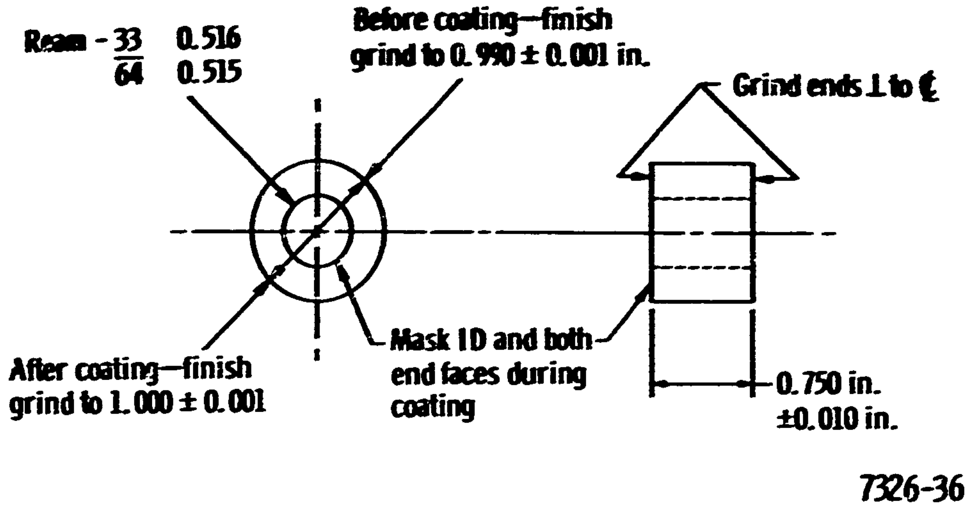


Figure 36. Tribometer rotating specimen.

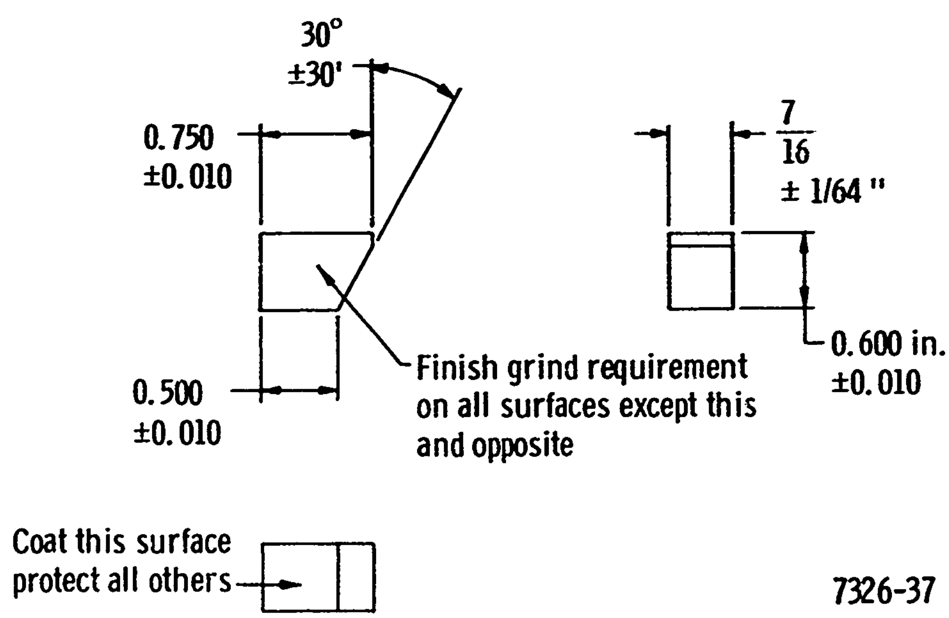


Figure 37. Tribometer stationary platen specimen.

The following test specimen sets were tested to determine the optimum material and lubricant coating combination to resist surface deterioration.

Plating	Surface lubricant coatings: None	$Ag-NbTe_2$	$Te-MoS_2$	$MoS_2-Sb_2O_3$
Iron	6	6	-	6
Iron-nickel	6	6	-	6
Electroless nickel	6	6	6	6

Typical Tribometer test specimen set is shown in Figure 38.

Electroless Nickel (Nichem) Hard Coating

The Ti 6Al-2Sn-4Zr-6Mo Tribometer cylinders and platens were plated with 18 to 24 mils of electroless nickel (Nichem), thermally diffused at 1000°F in vacuum, and finish ground to 15 mils of hard coating with a hardness of Rc 55 to 58.

Because of the extrusion and piling up around the wear scars of the Tribometer tests of the electroless nickel (Nichem) hard coatings, the electrophoretic Teflon-MoS_2 surface lubricant coating was dropped from further consideration for this program. Accordingly, Tribometer tests were performed with carbonitrided iron and iron-nickel alloys on the Ti 6Al-2Sn-4Zr-6Mo in the finish ground condition and with the spray-coated AFML (DC 1-3943) and the electrophoretic $Ag-NbTe_2$ solid lubricant coatings.

Carbonitrided Iron and Iron-Nickel Hard Coating

The program originally included the use of diffused electroless nickel (Nichem) as the bonding medium for the iron and the iron-nickel alloy hard coatings. Unfortunately, by the time it was

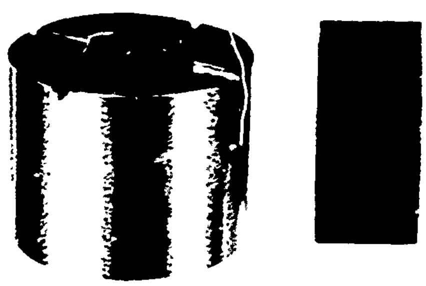


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Figure 38. Typical Tribometer test cylinder and platen.

learned that this bonding system would not survive the conditions of the carbonitriding heat treat cycles, all iron and iron-nickel alloy Tribometer specimens had been processed through plating with the nickel strike included. It therefore was decided to heat treat the specimens to determine if sufficient number with adequate bond would be available for the Tribometer tests. For a time this appeared to be true; however, as the tests were begun it was evident that the bonding system would not survive the Tribometer test loads. Figure 39 illustrates the failures experienced; the weak bond failed under applied load and the hard coatings fatigued and fractured catastrophically. Late in the program it was then necessary to produce iron and iron-nickel alloy Tribometer specimens which had been bonded by the thermal diffusion procedure.

Figure 40 and Figure 41 show the extreme limits of wear scar profiles with their test specimens.

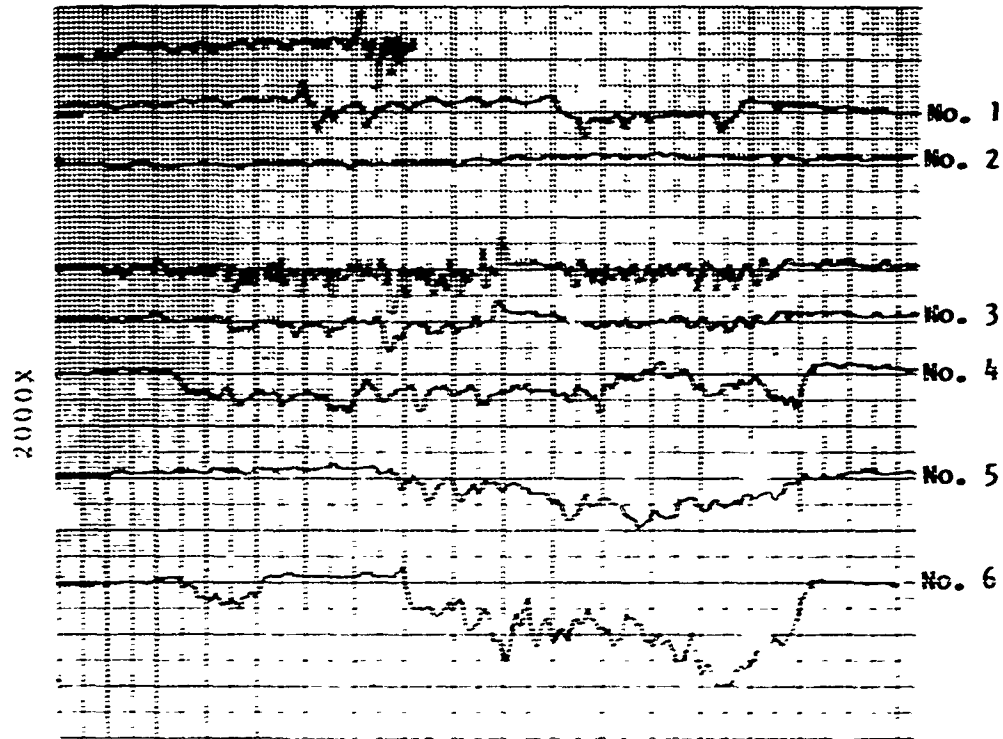
Table XIX is a summary of the wear scar depths and a summary of friction tests is shown in Figure 42.

<u>Tribometer Test Conclusions</u>

- Tribometer testing reveals little difference between vacuum diffused, double tempered, carbonitrided iron and iron-nickel as hard coating materials.
- The electrophoretic Teflon-MoS_2 surface lubricant shows good properties. However, this lubricant's appreciable alteration of surface geometry by extrusion displacement make it a questionable choice for highly loaded lubricated surfaces.
- AFML-41, surface lubricant provides optimum protection for all of the materials tested.
- Carbonitrided iron + AFML-41 produced the least surface disruption.

7326-39

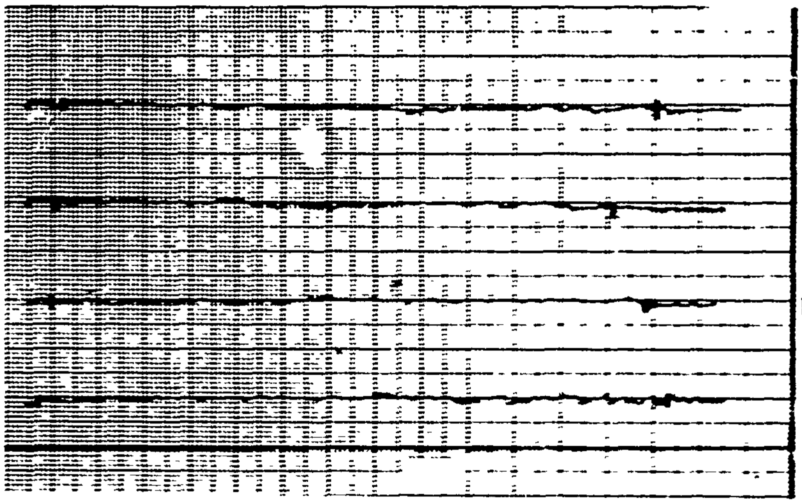
Figure 39. Typical failure Fe and Fe-Ni coating with electroless Ni bond medium.



32X

Magn: 2X

Figure 40. Results of Tribometer testing of bare finish ground electroless Ni.



32X

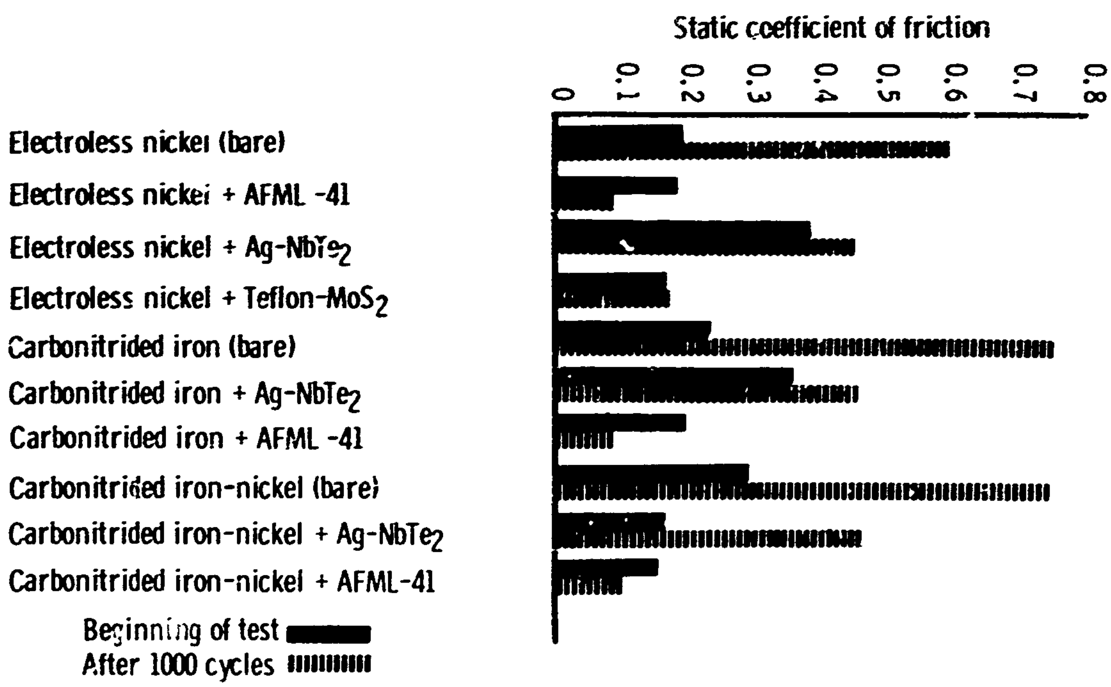
Magn: 2X

Figure 41. Results of Tribometer testing of carbonitrided Fe + AFML (DC1-3943).

Table XIX.

Summary of tribometer wear scars.

Condition	Wear scar depth (in.)
Electroless nickel (bare)	0.000290
Electroless nickel + AFML-41	0.000063
Electroless nickel + $Ag-NbTe_2$	0.000110
Electroless nickel + Teflon-MoS_2	0.000028
Carbonitrided iron (bare)	0.000048
Carbonitrided iron + $Ag-NbTe_2$	0.000026
Carbonitrided iron + AFML-41	0.000013
Carbonitrided iron-nickel (bare)	0.000026
Carbonitrided iron-nickel + $Ag-NbTe_2$	0.000077
Carbonitrided iron-nickel + AFML-41	0.000019



7326-42

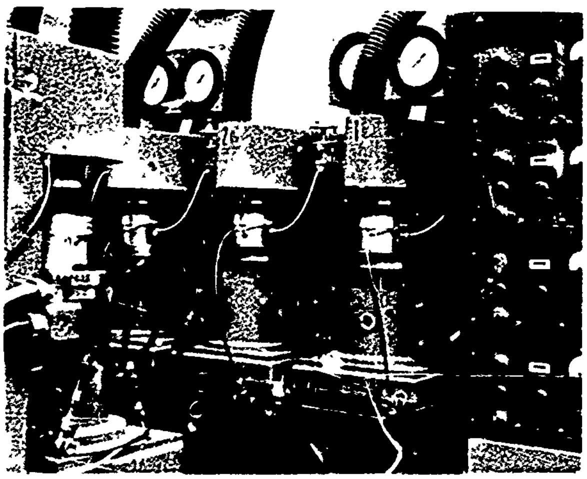
Figure 42. Summary of Tribometer friction testing.

THREE-BALL-AND-CONE TESTS

The DDA-designated three-ball-and-cone test facility consists of eight units for the evaluation of materials under high Hertzian rolling contact fatigue loads. Figure 43 is a view of the typical test rigs in DDA Materials Laboratories and Figure 44 shows a schematic of the rig system. The test facility consists essentially of a high speed shaft which holds and drives the test cone specimen; a bottom fixture which retains the three ball bearings and outer race; a temperature controllable positive pressure lubricating system; loading piston; and automatic shut-off controls. The test performed with this facility is comparable to the cyclic compressive or crushing load in gear and bearing usage. Both lubricated and oil-starved testing can be performed up to 600,000 psi Hertzian stress levels.

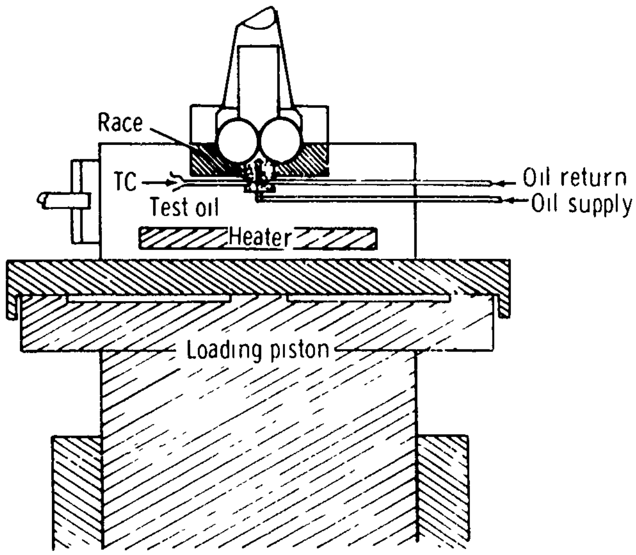
Test Parameters

● Test machine speed, rpm	10,770
● Stress cycles/hr	1,518,570
● Test cone surface finish, rms	4
● Total system vibration at origin of test, rms volts	max 0.3; optimum 0.1
● Contact ball permanent set	None
● Lubricant temperature, °F	190 to 200
● Lubricant	MIL-L-7808



7326-43

Figure 43. Three-ball-and-cone test rigs.



7326-44

Figure 44. Three-ball-and-cone fatigue tester schematic.

Cone Test Specimens, Figure 45 were manufactured with 15 mils of iron-nickel or electroless nickel plating over Ti 6Al-2Sn-4Zr-6Mo. The specimens were tested bare and with Ag-Nb-TeO_2 and MoS_2-SbO_3 lubricant coatings as follows.

Plating	Surface lubricant coating: None	Ag-$NbTe_2$	MoS_2-Sb_2O_3
Iron-nickel			
Single temper	8	-	-
Double temper	18	8	10
Electroless nickel	14	8	8

Figure 46 shows a finished test specimen together with the bearing balls and outer race used on the three-ball-and-cone tests.

The following cone fatigue tests shown in Tables XX, XXI, and XXII were run to determine the endurance limit of the various combination of materials and surface coatings.

Figure 47 is a summary of the cone fatigue tests which show their respective fatigue life values relative to AMS-6265 carburized steel.

A typical pitting fatigue failure is shown in Figures 48 and 49.

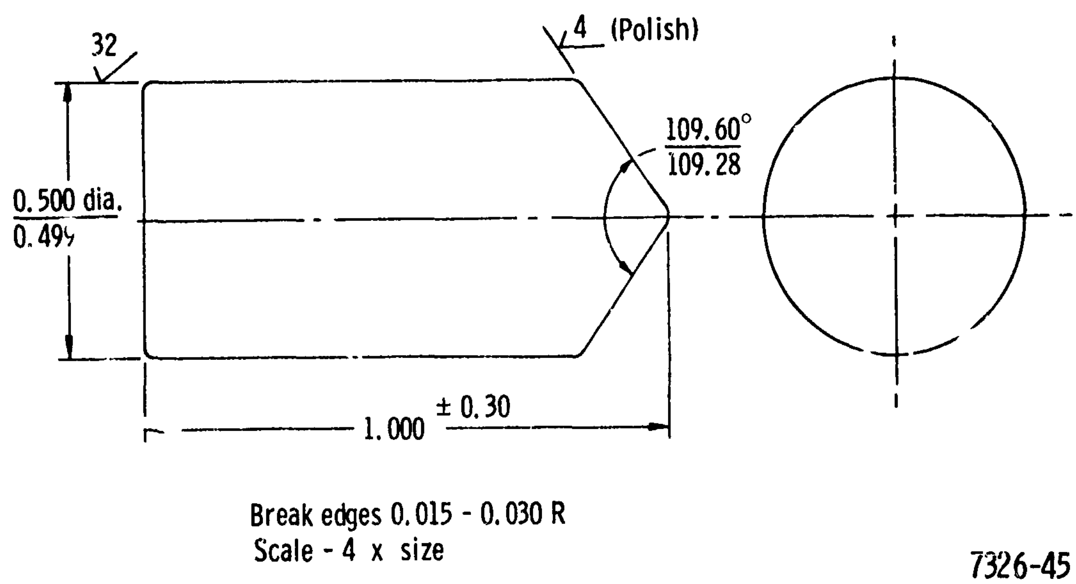
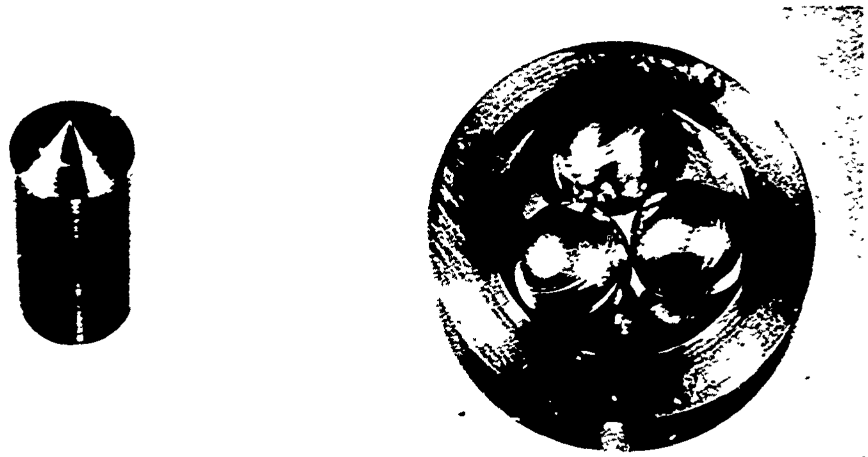
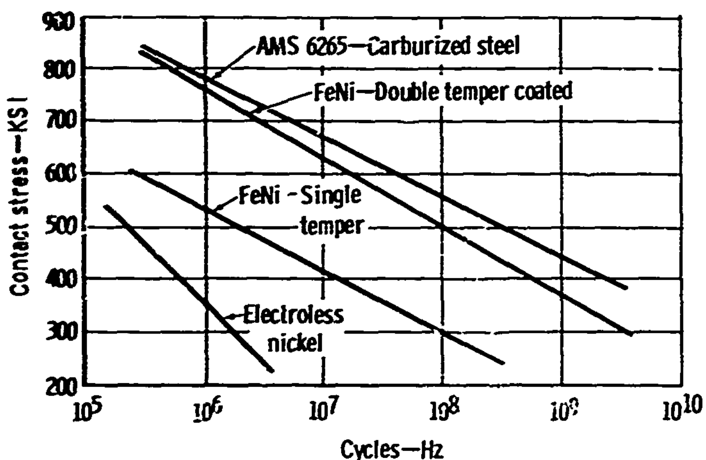


Figure 45. Three-ball-and-cone rig test specimens.



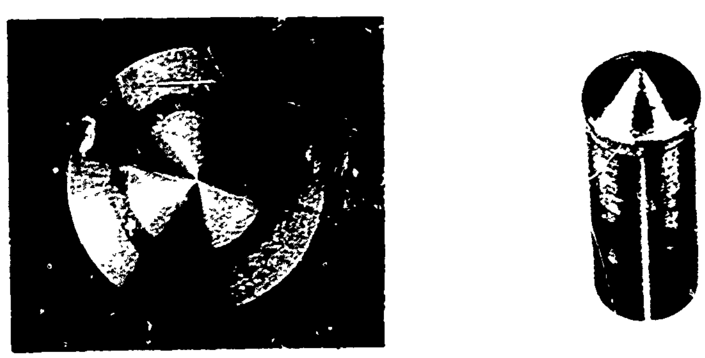
7326-46

Figure 46. Three-ball-and-cone test specimens.



7326-47

Figure 47. Three-ball-and-cone test summary.



7326-48

Figure 48. Typical cone specimen failure.

Table XX.

Three-ball-and-cone test results—iron-nickel alloy.

Specimen No.	Load level Hertizian (psi)	Stress cycles	Dispositon
Carbonitrided iron-nickel alloy vacuum diffused, single temper—lubricant: none			
4	600,000	3.9×10^5	Failed
6	600,000	3.1×10^5	Failed
2	500,000	6.8×10^6	Failed
5	500,000	4.2×10^6	Failed
7	400,000	1.5×10^7	Failed
8	400,000	6.9×10^7	**
1	300,000	4.0×10^8	Failed
3	300,000	1.0×10^8	**
Carbonitrided iron-nickel alloy vacuum diffused, double temper—lubricant: none			
11	600,000	2.5×10^8	Terminated
13	600,000	1.1×10^8	Terminated
14	600,000	3.1×10^8	Terminated
17	600,000	8.7×10^7	Terminated
20	600,000	2.5×10^5	**
21	600,000	2.6×10^8	Terminated
22	600,000	1.6×10^7	Failed
12	500,000	5.8×10^8	Terminated
23	500,000	6.9×10^8	Terminated
24	500,000	9.2×10^7	Failed
25	500,000	---	**
26	500,000	6.8×10^8	Terminated
9	400,000	1.1×10^9	Terminated
10	400,000	1.1×10^9	Terminated
Carbonitrided iron-nickel alloy vacuum diffused, double temper, peen—lubricant: none			
15*	600,000	7.7×10^5	Failed
16*	600,000	1.4×10^6	Failed
18*	600,000	5.7×10^6	Failed
19*	600,000	1.4×10^7	Failed

*Abnormally high vibration—surface finish: rms 15 to 17.

**Abnormal failures are those which show eccentric wear patterns, fail at test inception, or experience high initial vibration.

Table XXI.

Three-ball-and-cone test results—iron-nickel alloy and iron.

Specimen No.	Load level Hertizian (psi)	Stress cycles	Dispositon
Iron-nickel alloy vacuum diffused, double temper—lubricant: MoS_2-SbO_3			
3	600,000	1.1×10^8	Terminated
4	600,000	---	*
10	600,000	2.3×10^7	*
5	500,000	2.5×10^7	*
6	500,000	7.9×10^8	Terminated
7	500,000	4.7×10^8	Terminated
8	500,000	7.7×10^7	Failed
9	500,000	---	*
1	400,000	2.5×10^7	Failed
2	400,000	4.4×10^8	Failed
Iron-nickel alloy vacuum diffused, double temper—lubricant: Ag-Nb-Te_2			
1	600,000	---	*
2	600,000	---	*
3	600,000	---	*
4	600,000	1.8×10^8	Terminated
5	500,000	2.1×10^8	Terminated
6	500,000	5.7×10^8	Terminated
7	500,000	6.8×10^7	Terminated
8	500,000	6.8×10^7	Terminated

*Abnormal failures are those which show eccentric wear patterns, fail at test inception, or experience high initial vibration.

Oil Starvation Testing

Oil starvation testing attempts to shut-off the lubricant and create an oil starvation failure were unsuccessful. Residual lubrication was sufficient to allow test termination (over 1.0×10^8 stress cycles) on bare specimens without failure.

Three-Ball-And-Cone Test Conclusions

The following conclusions have been made concerning the compressive load capabilities of the systems based upon three-ball-and-cone testing. Also refer to Tables XX through XXII.

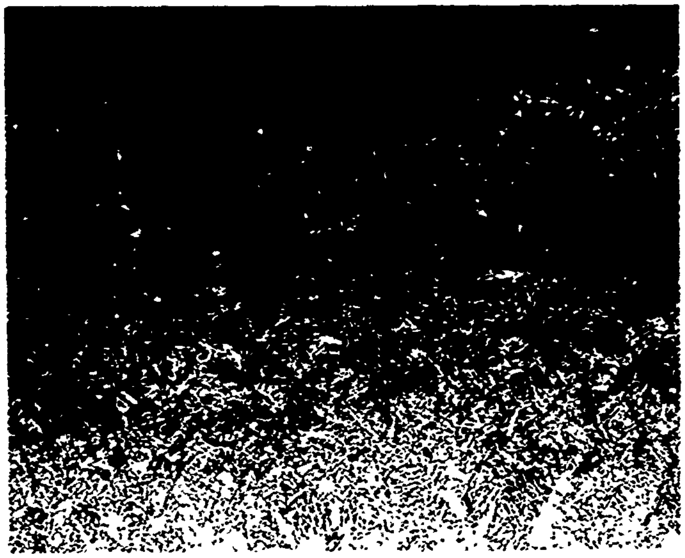
- The Nichem system has extensive scatter of results not attributable to test variations and is inferior to carbonitrided iron-nickel. Further pursuit of the Nichem system is not recommended at this time.

Table XXII.

Three-ball-and-cone test results—electroless nickel.

Specimen No.	Load level Hertizian (psi)	Stress cycles	Dispositon
Electroless nickel (Nichem) hardened and aged—lubricant: none			
1	600,000	1.3×10^4	Failed
2	600,000	1.3×10^4	Failed
11	500,000	7.2×10^5	Failed
12	500,000	6.1×10^8	Failed
14	500,000	3.7×10^5	Failed
5	400,000	4.9×10^5	Failed
6	400,000	2.5×10^8	Failed
9	400,000	5.0×10^7	Failed
10	400,000	9.2×10^7	Failed
3	300,000	1.4×10^6	Failed
4	300,000	1.4×10^6	*
7	300,000	4.8×10^4	*
8	300,000	6.1×10^7	Failed
13	300,000	7.6×10^8	Terminated
Electroless nickel (Nichem) hardened and aged—lubricant: MoS_2-SbO_3			
3	400,000	1.5×10^6	Failed
4	400,000	1.1×10^6	Failed
1	300,000	9.0×10^6	Failed
2	300,000	1.2×10^7	Failed
5	300,000	2.1×10^6	Failed
6	300,000	8.7×10^8	Failed
7	300,000	4.1×10^8	Failed
8	300,000	4.0×10^6	Failed
Electroless nickel (Nichem) hardened and aged—lubricant: Ag-Nb-Te_2			
1	300,000	3.1×10^7	Failed
2	300,000	1.3×10^6	Failed
3	300,000	1.5×10^8	Failed
4	300,000	3.5×10^6	Failed
5	300,000	2.8×10^6	Failed
6	300,000	3.2×10^6	Failed
7	300,000	3.6×10^6	Failed
8	300,000	---	*

*Abnormal failures are those which show eccentric wear patterns, fail at test inception, or experience high initial vibration.



7326-49

Figure 49. Typical microsection of pitting fatigue failure.

- The iron-nickel alloy system appears competitive with cased steel test results.
- Test termination to accomplish the greatest quantity of evaluations precludes determination of the maximum fatigue capabilities for the material. However, the data to depict minimum values.
- Double temper of the specimens is a definite improvement and is considered a direct asset to both bearing and gear life.
- Lubrication coatings do not appear to have any positive influence on three-ball-and-cone test specimens.

R. R. MOORE TESTS

Three groups of R. R. Moore test specimens were fabricated of Ti 6Al-2Sn-4Zr-6Mo. One group was tested bare after being processed through the thermal treatment that the gears would receive. The second group was iron plated and the third group was iron-nickel plated. Both plated groups were processed as shown in Table XXIII.

The R. R. Moore specimens as shown in Figure 50 were tested to establish their fatigue endurance limits. Test results are shown in Table XXIV.

Both iron and iron-nickel coated titanium show lower fatigue life than bare titanium, with relative summary shown in Figure 51.

Electron Microscope Analysis

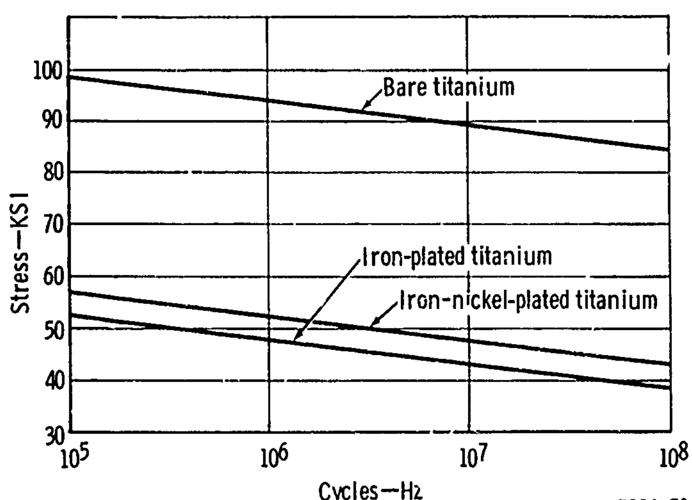
Representative fractures of each group are shown in Figure 52.

Table XXIII.
Thermal processing of R.R. Moore plated fatigue test specimens.

	Temperature (°F)	Time (hr)
Diffusion	1600	3
	Slow cool	
Carbonitride	1600	6
Quench	Oil	
Temper	350	1
	-100	1
	350	1
	500	12

7326-50

Figure 50. R. R. Moore test specimen.



7326-51

Figure 51. R. R. Moore fatigue test summary.

Table XXIV.

Results of R.R. Moore fatigue tests.

Condition	Stress (ksi)	Cycles X 10^6	Results
Bare Ti	100	0.046	Failed
	100	0.043	Failed
	90	6.587	Failed
	75	33.827	Terminated
	75	18.519	Terminated
	50	14.677	Terminated
	50	13.135	Terminated
	90	0.125	Failed
	90	9.022	Failed
Fe plated	100	---	Failed on load
	50	4.646	Failed on load
	50	0.075	Failed on load
	50	0.030	Failed on load
	45	4.354	Failed on load
	45	3.960	Failed on load
	40	59.037	Failed on load
FeNi plated	60	0.057	Failed
	55	1.061	Failed
	50	7.846	Failed
	50	2.945	Failed
	50	2.848	Failed
	40	63.578	Terminated
	40	37.276	Terminated

7326-52

Iron Iron-Nickel Bare Titanium

Figure 52. R. R. Moore test specimens.

Fractographic studies were made of both the iron and iron-nickel plated titanium specimens show the following results.

- **No striations typical of fatigue were present in either the Fe or Fe-Ni coating areas. Fatigue appears to initiate in the titanium at the interface below the coating.**
- **While the iron or iron-nickel coating appears to have failed in a simple overload at the beginning of the test, the subsurface titanium then progressed for a period in fatigue originating at or just below the diffusion zone.**

R. R. Moore Test Conclusions

- **Both iron and iron-nickel have lower fatigue capabilities than bare titanium.**
- **Fractographic studies indicate that fatigue appears to initiate in the titanium at the interface below the coating.**

CRUSHING TESTS

Crushing tests were performed to determine the effect of 2 mils of unhardened iron at the iron-titanium interface.

A block of Ti 6Al-2Sn-4Zr-6Mo was constructed and iron plated to a finish ground depth of approximately 0.015 inch. This surface was given a 2 hr carbonitride.

Subsequent load tests revealed the following:

Load, ksi	Deformation
300	Yes
275	Yes
250	Yes
225	Yes
200	Marginal
155	None

Subsequent examination revealed no indication of subsurface cracking in the areas of plastic deformation.

Crushing Test Conclusions

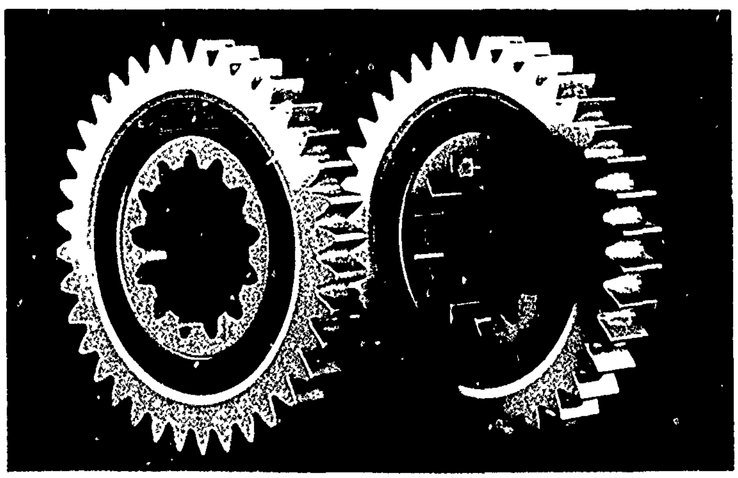
- Static Hertz crushing stress up to 200 ksi will not produce visual deformation of an iron plated surface of Rc 55 min hardness.
- Static Hertz crushing stress above 200 ksi produces permanent set of an iron plated surface of Rc 55 min hardness but will not cause subsurface cracking.

RYDER GEAR

Small-scale titanium gears submitted for Ryder Gear Machine testing during this program were grouped into three phases:

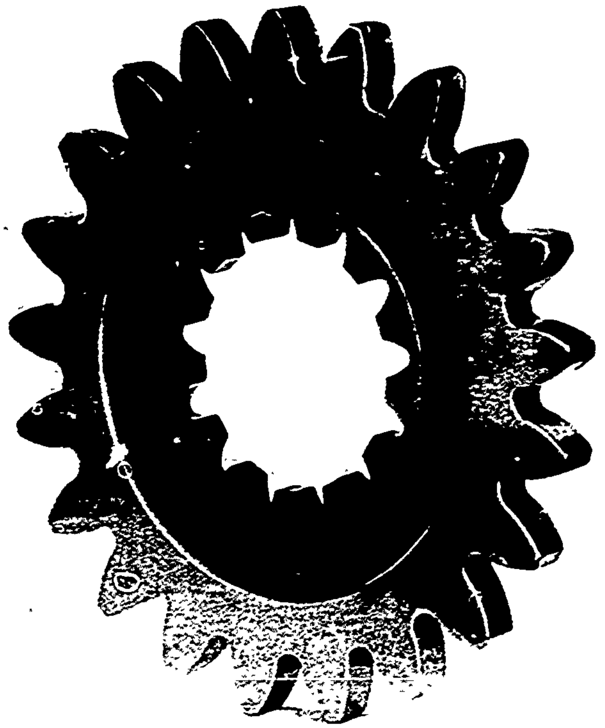
Phase I	Gear material: Ti 6Al-2Sn-4Zr-6Mo
	36 teeth, 10.29 pitch
	Hard coated with iron-nickel alloy
	Lubricant coated with AFML-41 (MoS_2-SbO_3)
Phase II	Gear material: Ti 6Al-2Sn-4Zr-6Mo
	21 teeth, 6.0 pitch
	Hard coated with iron
	Lubricant coated with AFML-41
Phase III	Gear material: Ti 6Al-2Sn-4Zr-6Mo
	21 teeth, 6.0 pitch
	Hard coated with iron
	Two sets lubricant coated with AFML-41
	One set black oxide surface treated

Typical Phase I and Phase II/III gear sets, before lubricant coating, are shown in Figures 53 and 54.



7326-53

Figure 53. Phase I type gear: 36 teeth, hard coated with Fe-Ni alloy.



7326-54

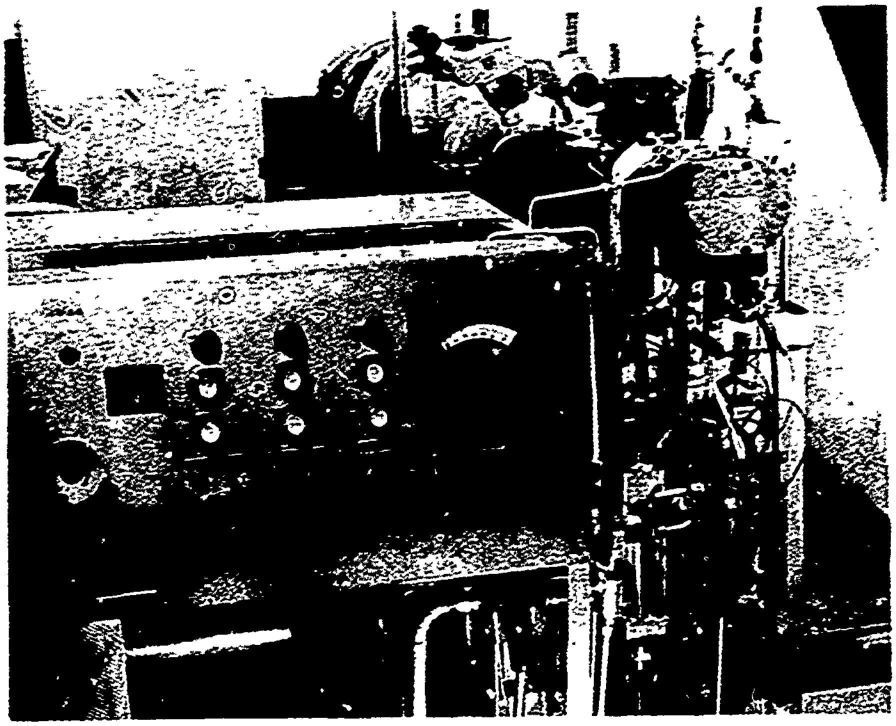
Figure 54. Phase II/III type gear: 21 teeth, hard coated with Fe.

Dynamic testing of the small-scale gears was conducted on a Ryder Gear Tester modified by DDA and consisted of the following major components:

- Ryder—ERDCO Universal Drive Stand and Control Console
- ERDCO Antifriction Ryder Gear Head, Model R-5589
- ERDCO—CRC Test Oil Cart, Model 2300S-2
- Moore "Nullmatic" Load Control System

The modified Ryder Gear Tester is capable of performance testing a wide variety of gear materials and designs, heat-treatment techniques, bonded coating materials, and coated and liquid lubricants.

Conditions simulating full-scale gear tooth crushing loads and tooth bending stresses can be readily applied and accurately maintained at temperatures up to 300°F. Equipment features are shown in Figure 55.



7326-55

Figure 55. Ryder—ERDCO gear tester with antifriction gear head and CRC oil cart.

Test Parameters

The following test parameters were maintained throughout the test program as specified:

- Test gear speed, rpm — 14,000 ±50
- Test oil specification — MIL-L-7808G
- Test oil flow rate, ml/min — *1,300 ±25
- Test oil in temperature, °F — 135 ±5
- Test oil system capacity, gal — 2
- Test oil filter, microns — 10
- Test gear load, psig — As shown ±0.25

*Increased to 1,600 ±25 during last three tests of Phase III gears.

Test Gear Load Schedules

The small-scale gear teeth scuffing and pitting fatigue limits were determined under conditions simulating full-scale gear teeth crushing loads and bending stresses. The Phase I gears were 36 teeth, and the Phase II/III gears were 21 teeth gears. The differences between the two gear designs necessitated two separate load schedules, and these are compared in Table XXV.

Table XXV.

Load schedules for small-scale titanium gears tested in Phases I and II/III.*

Phase	Test time (hr)		Torque (lb/in.)		Normal tooth load (lb)		Surface stress at pitch line (psi Hz)**	
	I	II/III	I	II/III	I	II/III	I	II/III
	10.0	2.0	470.3	176.2	296.5	111.1	105,930	79,430
	10.0	2.0	530.9	239.9	334.7	151.2	112,550	92,650
	10.0	2.0	595.2	313.3	375.3	197.5	119,170	105,910
	20.0	2.0	663.2	396.6	418.1	250.0	125,790	119,150
	20.0	2.0	734.9	489.9	463.3	308.7	132,410	132,380
	20.0	10.0	810.2	592.4	510.8	373.5	139,030	145,640
	20.0	10.0	889.2	705.1	560.6	444.5	145,650	158,870
	20.0	10.0	971.9	827.5	612.8	521.7	152,270	172,000
	20.0	10.0	1,058.2	959.7	667.2	605.1	158,890	185,370

*Phase I is a 36-tooth load schedule.
Phase II/III is a 21-tooth load schedule.

**Based upon Young's Modulus: 30.0×10^6.

Test Gear Inspection

The narrow test gear teeth were inspected under magnification upon the completion of each time/load increment, and after each equipment shut-down, whether scheduled or unscheduled. Gear teeth were evaluated on the bases of relative rate of tooth face scuffing, pitting fatigue, compression cracking of the hard coating, loss of hard coating, or other visually observable distress. Wide test gear teeth were inspected without magnification at the same time. Detailed metallurgical investigations were conducted on the gears only after test termination.

Ryder Gear Test Data

A tabular summary of each gear set installed and tested on the Ryder Gear Tester during this program, the maximum test time, and the condition of the gears at test termination is presented in Table XXVI. Detailed data recorded at each inspection of the gears will be found in Appendix III.

Metallurgy Analysis

Phase I Analysis

Test I.1—Tooth fracture of wide gear shown in Figure 56 progressed from surface blemish. Narrow gear showed only minor tooth scuffing.

Table XXVI.

Summary of Ryder gear tests conducted on small-scale gears during Phases I, II, and III.

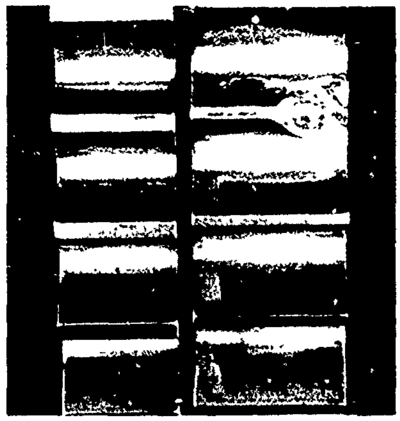
Test No.	Gear set No.	Gear width	Total time (hr)	Maximum stress (psi)	Gear condition at test termination
			Phase I		
1	1-A	Narrow	30.0	119,170	No failure, normal scuff wear only
	1-B	Wide			Tooth 35 broken; all others normal scuff wear
2	2-A	Narrow	14.0	105,930	Overtemperature due to lubrication loss
	2-A	Wide			Overtemperature due to lubrication loss
3	1-B	Narrow	10.0	105,930	Teeth 13-18 broken; others show impact damage
	2-B	Wide			Impact damage on numerous teeth
4	3-A	Narrow	2.5	86,100	Misalignment; excessive wear on all teeth
	3-A	Wide			Misalignment; excessive wear on all teeth
5	4-A	Narrow	17.4	112,550	Tooth 34 broken; plate loss on other tips
	4-A	Wide			Plate loss on tips of numerous teeth
			Phase II		
1	2-A	Narrow	6.0	105,910	Misalignment; no observable damage
	2-A	Wide			Misalignment; no observable damage
2	2-B	Narrow	12.5	158,870	Plate damage on teeth 6, 7, 12, 15, & 19
	2-B	Wide			Minor scuffing, no observable damage
3	3-A	Narrow	12.3	158,870	Plate loss on all teeth
	*2-A	Wide			Plate cracked on all teeth
			Phase III		
1	1-A	Narrow	1.0	79,430	Loose nut permitted misalignment; compression damage
	1-A	Wide			Misalignment; some compression damage
2	1-B	Narrow	0.1	79,430	Loose nut permitted misalignment; compression damage
	1-B	Wide			Misalignment; plate loss on teeth 10-13
3	2-A	Narrow	29.2	158,870	Tooth 7 plate loss; plate smeared on other teeth
	2-A	Wide			Plate smeared on numerous teeth
4	3-A	Narrow	19.5	145,640	Gear web fractured; minor scuffing on all teeth
	3-A	Wide			Minor scuffing on all teeth
5	2-B	Narrow	21.7	158,870	Tooth 7 broken; scuff damage on all teeth
	2-B	Wide			Minor scuff damage on all teeth
6	4-A	Narrow	8.0	119,150	Tooth 18 plate loss; minor scuffing on all teeth
	4-A	Wide			Minor scuffing on all teeth

Note: Phase I—Gear sets 1, 2, and 3 coated with iron-nickel alloy.
Gear set 4 coated with iron only.
Phases II/III—All sets coated with iron only.

*Previously used in Test 1 for 6.0 hours under load.

Test I. 2—Test rig failure causing loss of lubrication caused premature gear failure. No gear analysis made.

Test I. 3—Fracture of narrow gear teeth resulted from multiple indications of fatigue failure in the area of high nickel concentration in the tooth root fillet area. Figure 57 shows the fractured tooth failures.



7326-56

Figure 56. Wide gear tooth fracture.

7326-57

Figure 57. Fractured gear teeth induced by fatigue failure.

Test 1.4—Excessive wear encountered in break-in. The gears were reground to have 0.005-in. average coating thickness. When shot peened, the coating came off in the nickel-rich areas of the tooth flanks. The gears were not suitable for retesting.

Test 1.5—This gear set was plated with iron without nickel to eliminate the possibility of producing nickel rich areas of coating at the tooth flanks. It also resulted in thin coating thicknesses on these areas. Excess coating had to be removed to clean up the tooth profiles resulting in 0.005-in. plate thickness. The coating fractured at the tooth tips resulting from the stress concentration at the juncture of the thin tooth profile coating and the thick remaining coating on the tooth OD.

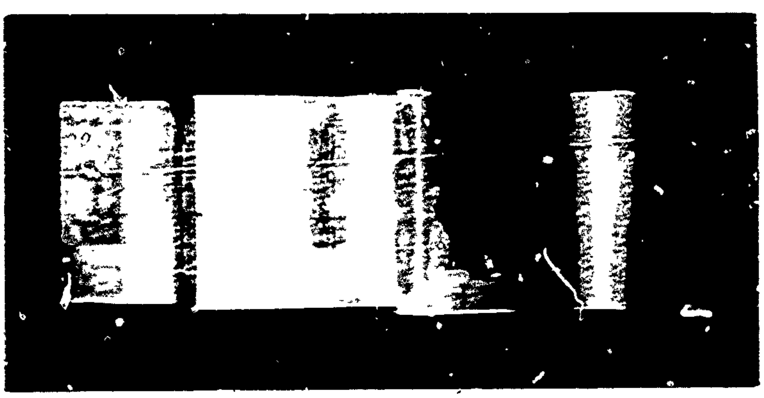
Phase II Analysis

Test 1—Axial mislocation of the narrow gear resulting in reduced contact is shown in Figure 58.

Test 2—Examination on the narrow gear revealed crack indications near the tips of four teeth. A section of case and some base material was spalled and the wide gear showed only light scuffing with no indication of heavy distress or cracking. The gears and damaged teeth are shown in Figure 59.

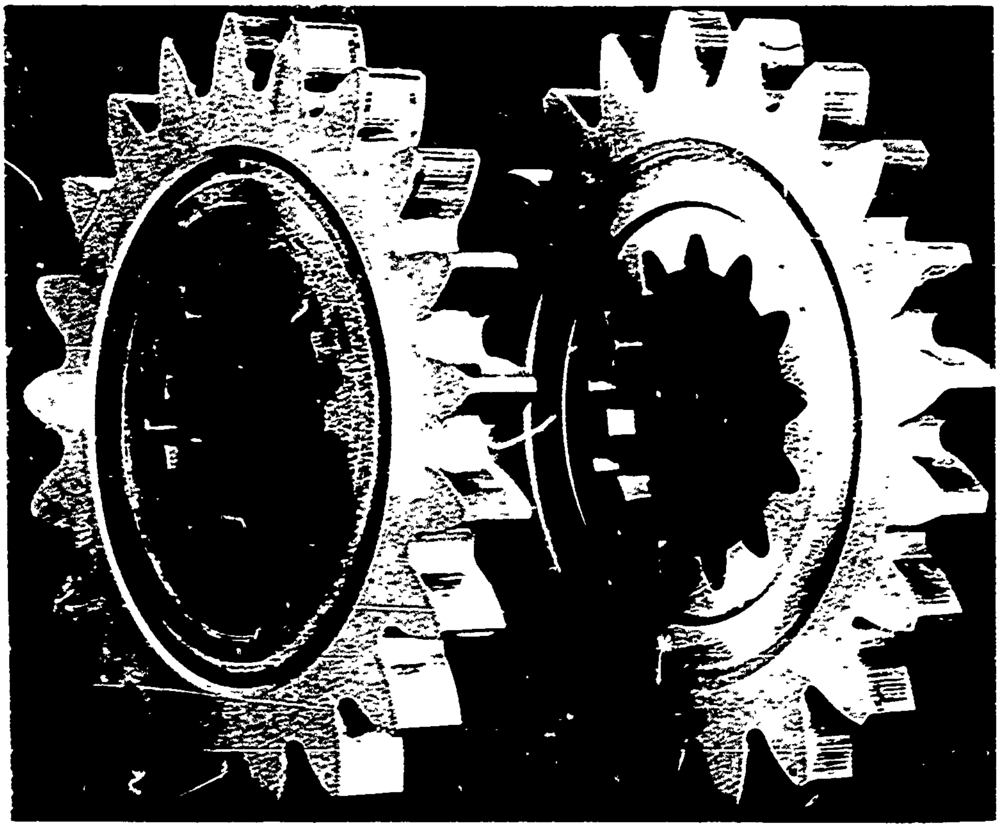
A macro section was cut through a narrow gear tooth as shown in Figure 60. The diffusion zone appears quite uniform with a depth of 0.0025–0.0035 inch. Case thickness measurements measured are as follows.

Location	Left side	Right side
OD break	0.014	0.0125
Pitch diameter	0.012	0.0115
Active profile diameter	0.012	0.0125
Root radius	0.0115	0.0115



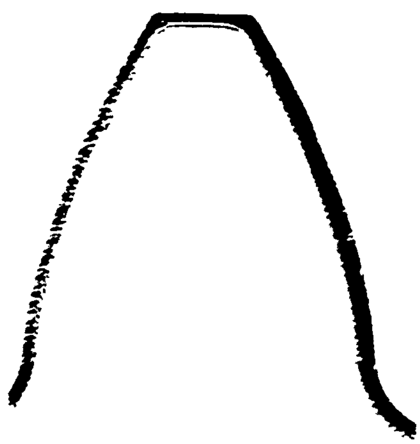
7326-58

Figure 58. Phase II.1 contact pattern of mislocated gear.



7326-59

Figure 59. Phase II. 2 gear tooth damage.



7326-60

Magn: 6X

Figure 60. Tooth plate thickness macro section.

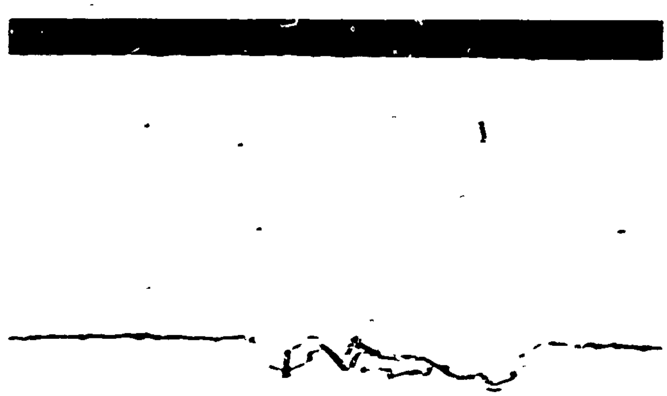
Fracturing of the iron was predominantly along a plane at the iron to titanium interface, see Figure 61. Microexamination revealed localized areas of diffusion zone cracking in a plane relatively parallel to the interface. In addition, light cracking of the iron plate was observed normal to the gear face.

Test 3—Heavy spalling and loss of case was noted on nearly every tooth of both gears as shown in Figure 62. Damage is attributed to poor bond of the iron coating.

Phase III Analysis

Test 1 and 2—The gears were installed with low retaining nut torque which resulted in fatigue failure of the lock washer tab. This allowed the lock nut to back off resulting in misalignment and damage to the gear teeth. The gears were turned over and the same assembly condition duplicated. A similar failure resulted as shown in Figure 63. Gear tooth damage is shown in Figure 64.

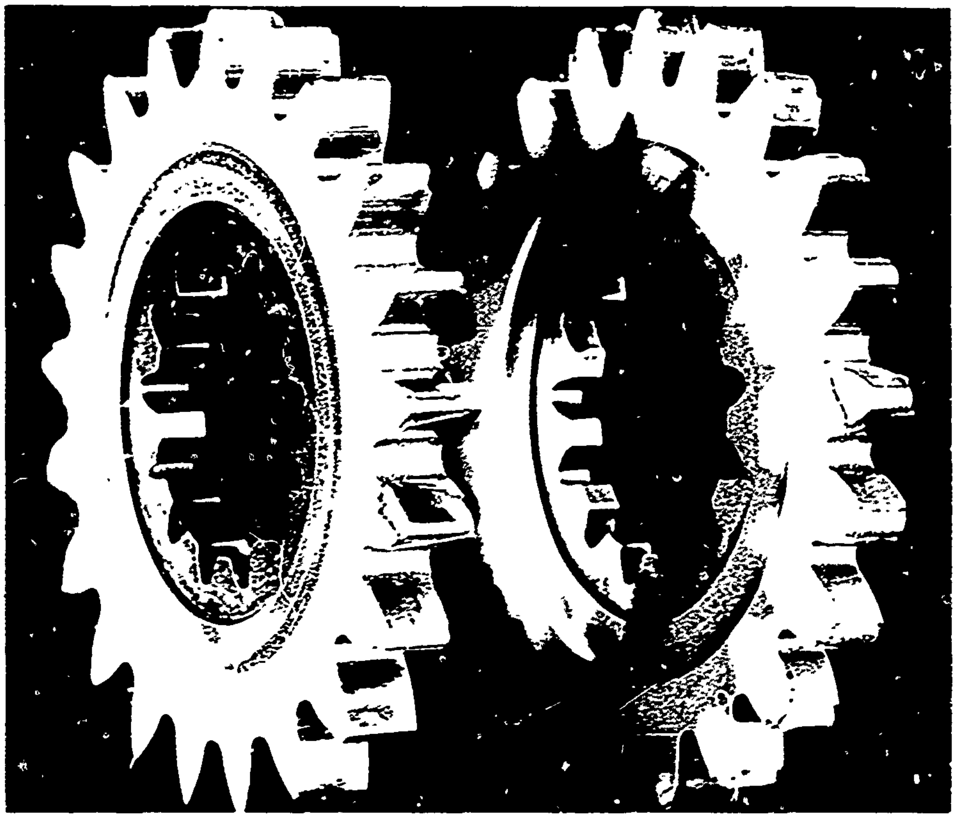
Test 3—Damage to the gears is shown in Figure 65. Photomicrograph typifying the narrow gear case structure is shown in Figure 66. Microexamination subsequent to test showed a plating line defect which led into the diffusion zone and provided a weak junction at which failure occurred.



7326-61

Mgn: 100X

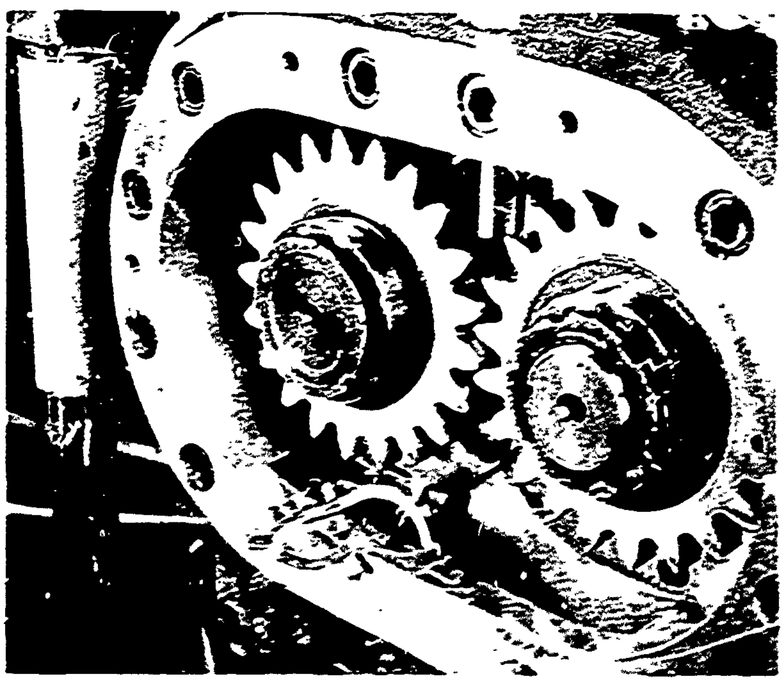
Figure 61. Photomicrograph of diffusion zone cracking



7326-62

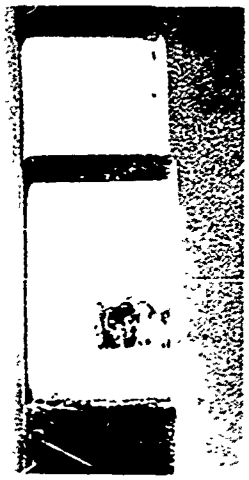
Mgn: 1X

Figure 62. Phase II.3 gear teeth damage.



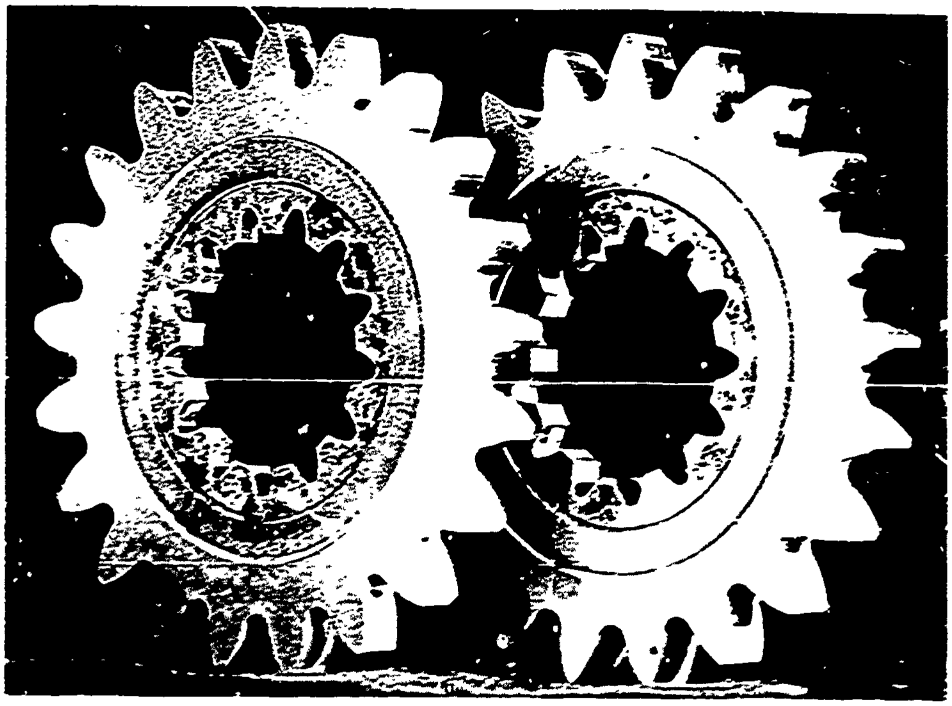
7326-63

Figure 63. View of gear tab lock failure.



7326-64

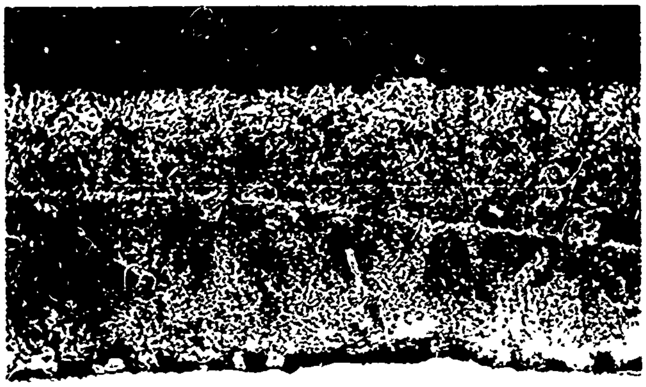
Figure 64. Phase III.1 and .2 gear damage by loose retaining nut.



7326-55

Figure 65. Phase III.3 test gear damage.

Test 4—Metallurgical examination revealed a fatigue gear web failure originating in a processing defect and progressing from the gear tooth root fillet toward the hub, see Figure 67.



7326-66

Figure 66. Phase III plating line defect.

7326-67

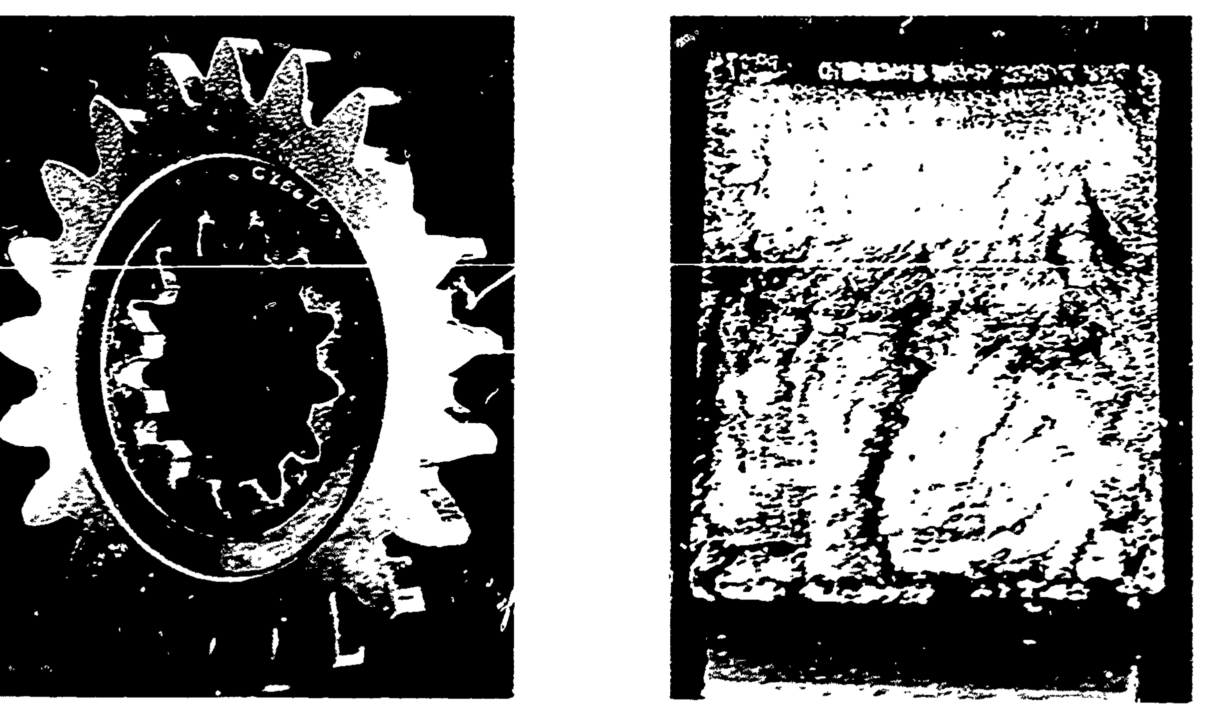
Figure 67. Gear web failure.

Test 5—Photomicrograph Figure 68 shows satisfactory case condition in areas adjacent to the tooth fracture.

Tooth failure of the narrow gear is shown in Figure 69. Fractographic analysis indicated no evidence of fatigue. The extremely rapid fracture is indicative of an overload such as foreign material going through mesh of the teeth.

7326-68

Figure 68. Case condition adjacent to failure.



7326-69

Figure 69. Phase III-5 test gear failure.

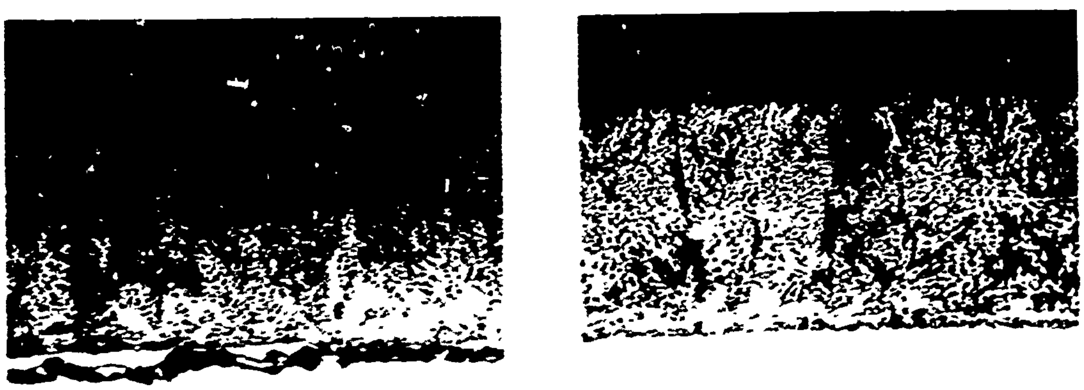
Test 6—Photomicrographs shown in Figure 70 are typical of the case structure. Surface spalling or fracturing is along the diffusion interface. Although fracturing is in the diffusion zone, titanium base metal can be seen breaking away with the iron case. The bond integrity in the gears is considered excellent.

Gear Test Summary

The common basis selected was 10^7 cycles to evaluate the fatigue strength of the test gears relative to hardened steel gears. Figure 71 shows the pitting fatigue stress level of the titanium gears relative to hardened steel gears. DDA experience design criteria for hardened steel gears is 242, 000 psi with a negative reciprocal slope value of the S/N curve of 12. 08. The AGMA standard 210. 02 allowable contact stress for 10^7 cycles is 180-225 ksi for Rc55-60 case hardness for steel gears.

The initial contract objective was to achieve 150 hr of operation or 126×10^6 stress cycles at 132, 000 psi (based on steel modulus of elasticity or 100, 000 psi based on titanium modulus of elasticity). This stress related to 10^7 stress cycles by the slope of the stress-cycle curve is 163, 000 psi.

As the program progressed the objective was established at stated loading cycles of different stress amplitudes starting at 105, 500 psi and progressing up to 158, 000 psi at 150 hr of test time. The cumulative damage in fatigue based on Miner's rule is 147, 300 psi at 150 hr or 181, 600 psi at 10^7 cycles.



7326-70

Figure 70. Photomicrographs typical of the case structure.

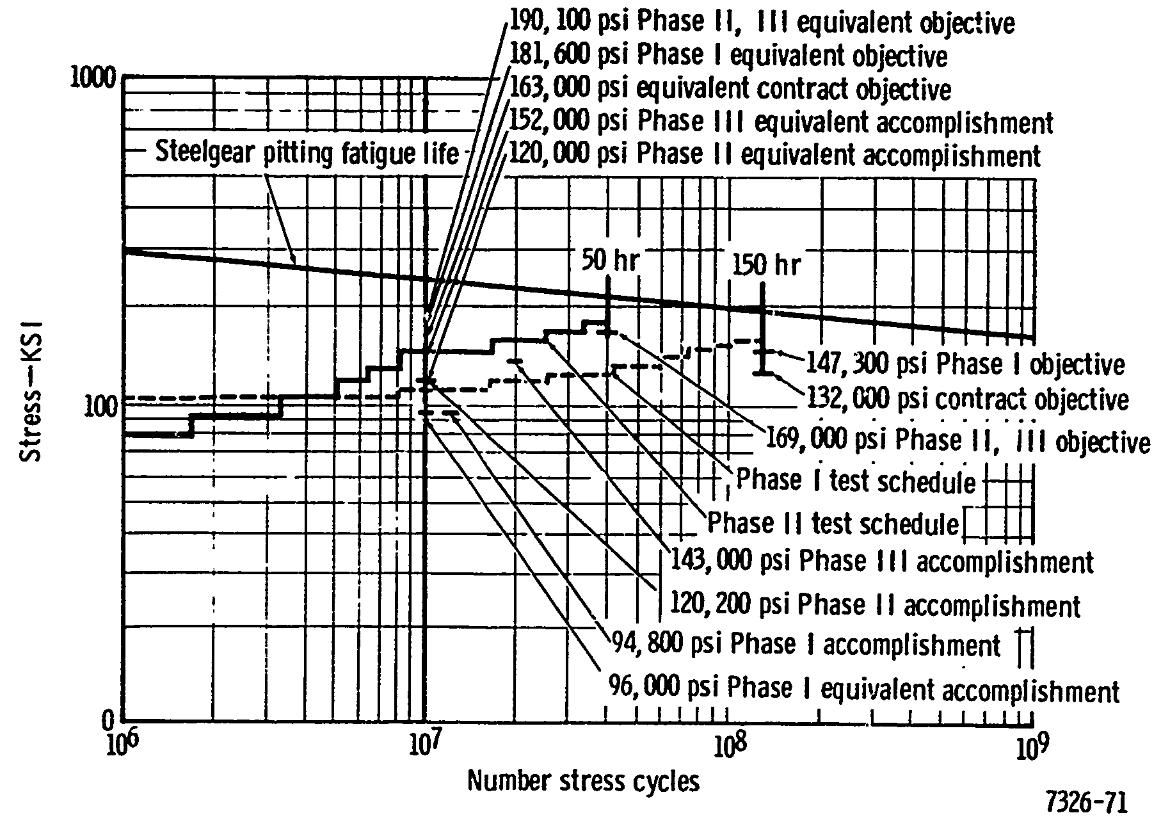


Figure 71. S/N test schedule.

Phase II and III objective was also a step loading with the stress amplitude starting at 79,500 psi and progressing up to 185,000 psi at 50 hr of test time. The cumulative fatigue damage at 50 hr is 169,000 psi or 190,100 psi at 10^7 cycles.

The average cumulative life of Phase I test results is 94,800 psi at 12.07×10^6 cycles or 96,000 psi at 10^7 cycles for Phase I.

Phase II average cumulative life is 120,200 psi at 9.9×10^6 cycles or 120,000 psi at 10^7 cycles.

Phase III average cumulative lif· is 143,000 psi at 19.9×10^6 cycles or 152,000 psi at 10^7 cycles.

The equivalent stress levels compared at 10^7 cycles are:

242,000 psi	DDA experience
180,000-225,000 psi	AGMA allowable
190,100 psi	Phase II and III objective

181,600 psi	Phase I objective
163,000 psi	Contract objective
152,000 psi	Phase III test achievement
120,000 psi	Phase II test achievement
96,000 psi	Phase I test achievement

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

The coated titanium gears achieved 93% of the initial contract objective or 63% of the fatigue strength of hardened steel gears. A review of the developed processes for hard coated titanium gears indicates:

- The plating procedure required excessive attention in the program and will continue to present a plating challenge due to the problem of obtaining equal plating distribution on the irregular geometry of the gear teeth
- The wear surfaces of carbonitrided iron were excellent and appear to be comparable with hardened steel gears
- The predominate failure mode of the tested gears was at the interface of the iron and titanium
- Specimen testing displayed excellent compressive strength properties for iron-coated titanium
- Model shop fabrication costs for titanium gears was 20% greater than hardened steel gears

It is recommended that further exploration of iron-plated coatings be attempted to develop added strength and ductility in the diffusion zone by solid solution forming elements at the interface. The relative improvement should be explored by free-free bending tests followed by additional Ryder gear manufacture and test.

Since iron-coated titanium three-ball-and-cone tests showed a pitting fatigue strength comparable to hardened steel, it is recommended that a program be initiated to adapt this process to rolling element bearing inner and outer races and their rolling elements, titanium shaft splines, and to the technology of making bearing races integral with titanium shafting by the iron coating process.

Appendix I

COMPUTER OUTPUT OF THE DDA GEAR DESIGN PROGRAM

```
                EXTERNAL SPUR OR HELICAL GEAR DATA

                PROGRAM NUMBER          DSAL-13
                PROGRAM COMPLETED       07/03/67
                PROGRAM REVISED         09/30/70
                CHANGE LETTER           A
                THE CURRENT DATE IS       72/054

                      I N P U T   D A T A   S E C T I O N

USERS                         DEPT.   PROJECT    EDO          NO. OF    LONG OR
NAME                          NO.     NO.        NO.          COPIES    SHORT FORM
   CHAPLIN, M.R.              7392    P153-2     AX186027     1         LONG

NO. OF TEETH  PRESSURE      DIAMETRAL     HELIX        HORSE-     RPM          BACKLASH        OPERATING CTR
PINION GEAR   ANGLE-PHIN    PITCH -PND    ANGLE -PSI   POWER      PINION       MIN     MAX     DISTANCE
  21    21    25.0000000    6.0000000     0.0          213.1900   14000.3000   0.0150  0.0180   0.0

      MATERIAL        E = MODULAS  MU  = RATIO   ENDURANCE LIMIT (PSI)   DESIGN LIMIT     (PSI)
PINION      GEAR   PINION  GEAR  PINION  GEAR    SC           SB          SC          SB
FE-II       FE-II   26.50  15.50  0.350  0.350   0.0          0.0         0.0         0.0

 TOLERANCE       MAX EDGE  MAX TIP          DELTA  T            DELTA  D  FACE WIDTH  -  MIN        FACE WIDTH  PIN
OD       ROOT    BREAK     BREAK    PINION            GEAR                PINION            GEAR   TOLERANCE   DIA
0.0015  0.0015   0.0200    0.0050   0.01500000 -0.01500000      NO        0.29000000  0.39600000  0.0040      0.0

  ADDENDUM  FACTOR         DEDENDUM  FACTOR       ROOT FILLET RADIUS  MAXIMUM    FACE BEVEL ANGLE  CROWNED  CROWN
PINION           GEAR   PINION            GEAR  PINION        GEAR  UNDERCUT   PINION     GEAR               AMOUNT
1.00000000 1.00000000  1.25000000 1.25000000    0.0           0.0   0.0        0.0        0.0      NO        0.0

HOUSING   OIL INLET    OIL           PLOT OR SCALE
MATERIAL  TEMPERATURE  VISCOSITY     OUTPUT
               0.0        0.0        PLOT        20
```

SPUR GEAR DATA
STANDARD CENTER DISTANCE
ADJUSTED ARC TOOTH THICKNESS

G E N E R A L   D A T A   S E C T I O N

GEAR RATIO	1/GEAR RATIO
1.00000000	1.00000000

	NORMAL PLANE	PLANE OF ROTATION	NON STD CENTERS
DIAMETRAL PITCH	6.00000000	6.00000000	6.00000000
PRESSURE ANGLE	25.00000000	25.00000000	25.00000000
SIN	0.42261826	0.42261826	0.42261826
COS	0.90630779	0.90630779	0.90630779
TAN	0.46630766	0.46630766	0.46630766
RADIANS	0.43633231	0.43633231	0.43633231
INVOLUTE	0.02997535	0.02997535	0.02997535
CIRCULAR PITCH	0.52359878	0.52359878	0.52359878
BASIC ARC TOOTH THK	0.26179939	0.26179939	0.26179939
BASE CIRCULAR PITCH	0.47454165	0.47454165	0.47454165

D E T A I L   D A T A   S E C T I O N

	PINION	GEAR
NUMBER OF TEETH - ACTUAL	21	21
- VIRTUAL	21.00000000	21.00000000
PITCH DIAMETER - STANDARD	3.50000000	3.50000000
- OPERATING . . .	3.50000000	3.50000000
- VIRTUAL	3.50000000	3.50000000
DELTA T	0.01500000	-0.01500000
DELTA D	0.0	0.0
ADDENDUM FACTOR	1.00000000	1.00000000
ADDENDUM STANDARD	0.16666667	0.16666667
ADDENDUM BALANCED	0.16666667	0.16666667
DEDENDUM FACTOR	1.20000000	1.20000000
DEDENDUM STANDARD	0.20000000	0.20000000
DEDENDUM BALANCED	0.20000000	0.20000000
ARC TOOTH THK. AT THE OPERATING PITCH DIAMETER - MIN .	0.26779939	0.23779539
- MAX .	0.26929939	0.23929939
ROOT FILLET RADIUS - MIN .	0.07267959	0.08992225
- MAX .	0.07335256	0.09059377
DIMENSION OVER TWO 0.28800 DIA PINS - MIN .	3.90151576	3.84387461
- MAX .	3.90432044	3.84633771
DIMENSION OVER ONE 0.28800 DIA PIN - MIN .	1.55582511	1.92692272
- MAX .	1.55723038	1.92540842

MISCELLANEOUS DATA SECTION

ROOT FILLET COORDINATES - PINION

CENTER LINE REFERENCE TOOTH X	TOOTH Y	SPACE X	SPACE Y	CONDITION	POINT OF TANGENCY WITH INVOLUTE DIAMETER	CENTER LINE TOOTH REFERENCE X	Y
0.24094597	1.60463168	0.00091209	1.62267973	MIN RF MAX DR	3.21778222	0.16841420	1.60005227
0.24163154	1.60451039	0.00020715	1.62260265	MAX RF MIN DR	3.21743395	0.16842542	1.59987599
0.24099408	1.60392304	0.00075040	1.62192981	MIN RF MIN DR *	3.21659177	0.16845206	1.59944977
0.24159219	1.60527627	0.00037009	1.62335262	MAX RF MAX DR	3.21862461	0.16838659	1.60047869

ROOT FILLET COORDINATES - GEAR

CENTER LINE REFERENCE TOOTH X	TOOTH Y	SPACE X	SPACE Y	CONDITION	POINT OF TANGENCY WITH INVOLUTE DIAMETER	CENTER LINE TOOTH REFERENCE X	Y
0.24311848	1.62130098	0.00131385	1.63992173	MIN RF MAX DR	3.23979567	0.15372264	1.61208520
0.24381584	1.62161722	0.00359867	1.63984366	MAX RF MIN DR	3.23840032	0.15374436	1.61188456
0.24320153	1.62103014	0.00112594	1.63917188	MIN RF MIN DR *	3.23760550	0.15378771	1.61148121
0.24372979	1.62239824	0.00079685	1.64059358	MAX RF MAX DR	3.23959033	0.15367855	1.61248854

	PINION	GEAR
ACTIVE PROFILE DIAMETER CALCULATED AT		
1. TIGHT MESH	3.25105997	3.25105997
2. OPERATING CENTERS	3.27288318	3.27288318
ANGLE BETWEEN ORIGIN OF INVOLUTE AND CENTER LINE OF TOOTH - DEGREES		
MIN	6.10139639	5.61028971
MAX	6.12595172	5.63484504
ANGLE BETWEEN ORIGIN OF INVOLUTE AND CENTER LINE OF SPACE - DEGREES		
MIN	2.44547685	2.93658353
MAX	2.47003218	2.96113886
ANGLE BETWEEN CENTER LINE OF TOOTH AND CENTER LINE OF SPACE	5.57142857	8.57142857

* * * * * * * * * * * * * * * * * *

ARC OF APPROACH - DEGREES	11.76726991
ARC OF RECESSION - DEGREES	11.76726991
CENTER DISTANCE - TIGHT MESH	3.43044456
LINE OF CONTACT LENGTH - MIN	0.65253089
LINE OF CONTACT LENGTH - MAX	0.72001621
HELICAL DELTA ANGLE	0.0
RPM - PINION	14000.000
RPM - GEAR	14000.000

* ROOT FILLET CONDITION USED IN THE BENDING STRESS CALCULATIONS

MISCELLANEOUS DATA SECTION

ROOT FILLET COORDINATES - PINION

CENTER LINE REFERENCE TOOTH X	TOOTH Y	SPACE X	SPACE Y	CONDITION	POINT OF TANGENCY WITH INVOLUTE CENTER LINE TOOTH REFERENCE DIAMETER	X	Y
0.24094597	1.60459166	0.00091269	1.62267973	MIN RF MAX DR	3.21778222	0.16841420	1.60005227
0.24163154	1.60431039	0.00020715	1.62260265	MAX RF MIN DR	3.21743395	0.16842542	1.59987599
0.24099406	1.60392504	0.00075049	1.62192981	MIN RF MIN DR *	3.21659177	0.16845206	1.59944977
0.24159219	1.60527627	0.00037003	1.62335262	MAX RF MAX DR	3.21862461	0.16838659	1.60047869

ROOT FILLET COORDINATES - GEAR

CENTER LINE REFERENCE TOOTH X	TOOTH Y	SPACE X	SPACE Y	CONDITION	POINT OF TANGENCY WITH INVOLUTE CENTER LINE TOOTH REFERENCE DIAMETER	X	Y
0.24311648	1.62190098	0.00131365	1.63902173	MIN RF MAX DR	3.23879567	0.15372264	1.61208520
0.24331364	1.62161722	0.00059867	1.63994366	MAX RF MIN DR	3.23840032	0.15374438	1.61188456
0.24320153	1.62103014	0.00111594	1.63917188	MIN RF MIN DR *	3.23760550	0.15378771	1.61148121
0.24372474	1.6223[illegible]	0.00079685	1.64059353	MAX RF MAX DR	3.23959033	0.15367855	1.61248854

	PINION	GEAR
ACTIVE PROFILE DIAMETER CALCULATED AT		
1. TIGHT MESH	3.25105977	3.25105997
2. OPERATING CENTERS	3.27288318	3.27288318
ANGLE BETWEEN ORIGIN OF INVOLUTE AND CENTER LINE OF TOOTH - DEGREES		
MIN	6.10129639	5.61028971
MAX	6.12595172	5.63484504
ANGLE BETWEEN ORIGIN OF INVOLUTE AND CENTER LINE OF SPACE - DEGREES		
MIN	2.44547685	2.93658353
MAX	2.47003219	2.96113836
ANGLE BETWEEN CENTER LINE OF TOOTH AND CENTER LINE OF SPACE	5.57142857	8.57142857

* * * * * * * * * * * * * * * * * *

ARC OF APPROACH - DEGREES	11.78726991
ARC OF RECESSION - DEGREES	11.78726991
CENTER DISTANCE - TIGHT MESH	3.43044456
LINE OF CONTACT LENGTH - MIN	0.65253089
LINE OF CONTACT LENGTH - MAX	0.72001621
HELICAL DELTA ANGLE	0.0
RPM - PINION	14300.000
RPM - GEAR	14300.000

* ROOT FILLET CONDITION USED IN THE BENDING STRESS CALCULATIONS

E V A L U A T I O N   S E C T I O N

PROFILE CONTACT RATIO	- MIN	1.37518149		
	- MAX	1.41948516		
FACE CONTACT RATIO	- MIN	0.0		
	- MAX	0.0		
PITCH LINE VELOCITY	- FT/MIN . . .	12828.17000216		
SLIDING VELOCITY	- FT/MIN	RELATIVE	PINION	GEAR
	- BC	4783.66781022	3029.58504809	7813.25285831
	- BSTC	2173.47616668	4334.68086956	6508.15703654
	- PITCH	0.0	5421.41895320	5421.41895320
	- ESTC	2173.47616668	6508.15703654	4334.68086986
	- EC	4783.66781022	7813.25285831	3029.58504809

TORQUE	- LB INS . . .	959.73569643
TANGENTIAL LOAD	- LBS	548.42039736
SEPARATING FORCE	- LBS	255.73253146
AXIAL FORCE	- LBS	0.0
NORMAL TOOTH LOAD	- LBS	605.11495742
	- LBS/IN FACE	
	- PINION . . .	2086.60330144
	- GEAR	1528.05807429

HERTZ SURFACE STRESS
EFFECTIVE FACE WIDTH = 0.25000000

	PINION		GEAR
PITCH (OP)	140000.2824	PITCH (OP)	140000.2824

BENDING STRESS - LEWIS

FACE WIDTH = 0.29000000		FACE WIDTH = 0.39600000	
	PINION		GEAR
BC (LPC)	4735.0322	BC (HPC)	22922.3414
BSTC (LPSTC)	7634.6166	BSTC (HPSTC)	14811.4030
PITCH (STD)	11772.6336	PITCH (STD)	9725.8994
PITCH (OP)	11772.6336	PITCH (OP)	9725.8994
ESTC (HPSTC)	17524.0320	ESTC (LPSTC)	6136.6469
EC (HPC)	26585.9830	EC (LPC)	3696.1082

D R A W I N G   D A T A   S E C T I O N

PINION

SPUR GEAR DATA
6.000000 NORMAL DIAMETRAL PITCH 21 TEETH
25.000000 NORMAL PRESSURE ANGLE
DISTANCE OVER TWO 0.28800 DIA PINS= 3.90152
3.90432
DISTANCE OVER ONE 0.28800 DIA PIN = 1.95583
1.95723

ROOT DIA = 3.098500 - 3.100000
PITCH DIA = 3.500000
OUTSIDE DIA = 3.831833 - 3.833333
ACTIVE PROFILE OUTSIDE 3.251060 DIA
FACE WIDTH = 0.290000 - 0.294000
MAX EDGE BREAK= 0.020000
MAX TIP BREAK = 0.005000
MIN TRUE FILLET RADIUS= 0.072680
MAX TRUE FILLET RADIUS= 0.073353
GEAR TOOTH ELEMENTS SHALL BE IN ACCORDANCE WITH EDI-
REFERENCE
ARC TOOTH THICKNESS IN PLANE OF ROTATION AT PD = 0.267799 - 0.269299
0.0150 TO 0.0180 BACKLASH WITH MATING GEAR ON 3.500000 CENTERS
BASE CIRCLE DIA = 3.172077

D R A W I N G   D A T A   S E C T I O N

GEAR

SPUR GEAR DATA
6.000000 NORMAL DIAMETRAL PITCH 21 TEETH
25.000000 NORMAL PRESSURE ANGLE
DISTANCE OVER TWO 0.28800 DIA PINS= 3.84387
3.84684
DISTANCE OVER ONE 0.28800 DIA PIN = 1.92692
1.92841

ROOT DIA = 3.098500 - 3.100000
PITCH DIA = 3.500000
OUTSIDE DIA = 3.831833 - 3.833333
ACTIVE PROFILE OUTSIDE 3.251060 DIA
FACE WIDTH = 0.396000 - 0.400000
MAX EDGE BREAK= 0.020000
MAX TIP BREAK = 0.003000
MIN TRUE FILLET RADIUS= 0.089922
MAX TRUE FILLET RADIUS= 0.090594
GEAR TOOTH ELEMENTS SHALL BE IN ACCORDANCE WITH EDI-
REFERENCE
ARC TOOTH THICKNESS IN PLANE OF ROTATION AT PD = 0.237799 - 0.239299
0.0150 TO 0.0180 BACKLASH WITH MATING GEAR ON 3.500000 CENTERS
BASE CIRCLE DIA = 3.172077

DEFLECTION SECTION

```
NG= 21.      RDG=    3.500000    RBGI=    3.098500    TNG=    0.237790    AG=    0.166667    FG=    0.396000
NP= 21.      RDP=    3.500000    RBPI=    3.098500    TNP=    0.267739    AP=    0.166667    FP=    0.290000
TP=    959.735096    PN=    6.000000    CDI=    3.500000    PHI=    25.000000    PSI=    0.0

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

NECG=  21.00    NEQP=  21.00    REQG=  1.7500000    REQP=  1.7500000    RBECG=  1.5960386    RBEQP=  1.5960386

BPK= 0.52360   SNPSB= 0.0    SNPHH=  0.42261826   ROG=  1.9166667   PB= 0.47454   ROP=  1.9166667   WOP=  2086.6

WOG=  1525.1    CD=   3.5000000    RRG=  1.54925    RRP=  1.54925

TBBG= 0.31060    TARG= 0.0    TBBP= 0.33779    TBRP= 0.0    CREQ= 1.418    CRP= 1.418    CRH= 0.0

CPSTCP=  1.69630    HPSTCP=  1.91263    LPM= -0.32786    HPM=  0.82786

* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *

RP(X)= EQUIVALENT PINION CONTACT RADIUS, PIN RAD= ACTUAL PINION CONTACT RADIUS
DEFP= PINION DEFLECTION IN PLANE OF ROTATION
DEFG= GEAR DEFLECTION IN PLANE OF ROTATION
DEFH= HERTZIAN DEFLECTION IN PLANE OF ROTATION
TOT DEF= TOTAL DEFLECTION OF GEAR AND PINION IN PLANE OF ROTATION
MODULE= LINE OF ACTION DISTANCE, PITCH POINT TO CONTACT POINT. ONE MODULE= 1/DIAMETRAL PITCH
CTP,OTG,OTH ARE DEFLECTION COEFFICIENTS. DEFP= OTP(WOP/E). WOP= LINE OF ACTION LOADING, LB/IN OF FACE WIDTH
```

EQUIVALENT RADIUS		DEFLECTION COEFFICIENTS - TOT			- - - DEFLECTION (PLANE OF ROTATION) - -			
PINION	GEAR	PINION	GEAR	HERTZIAN	PINION	GEAR	HERTZIAN	TOTAL
1.63900225	1.91951657	2.01525826	13.65788618	2.53477800	0.00025466	0.00126856	0.00037194	0.00189526
1.64834134	1.59124972	2.10479642	11.54395224	2.67364729	0.00025616	0.00106909	0.00039221	0.00172746
1.65939252	1.87212726	2.21092526	9.90761078	2.76490633	0.00027960	0.00091755	0.00040560	0.00160274
1.66914295	1.55345441	2.31579684	8.60349956	2.82905342	0.00029539	0.00079677	0.00041501	0.00150716
1.55057571	1.83523244	2.48126274	7.53507951	2.87575389	0.00031376	0.00069820	0.00042186	0.00143394
1.69268739	1.81762654	2.63091605	6.64794309	2.91025255	0.00033524	0.00061567	0.00042692	0.00137782
1.71598567	1.78259320	2.86605295	5.21277754	2.95502416	0.00037153	0.00048276	0.00043349	0.00130777
1.75000001	1.75000000	3.69924624	4.13256591	2.97349893	0.00046781	0.00038744	0.00043620	0.00129145
1.76259329	1.71348557	4.51354784	3.43660031	2.97041666	0.00057155	0.00031826	0.00043574	0.00132555
1.81762654	1.69268739	5.64437016	2.89123063	2.94463777	0.00071375	0.00026776	0.00043196	0.00141348
1.83523244	1.55057571	5.33091243	2.63470534	2.92223676	0.00080061	0.00024574	0.00042867	0.00147792
1.65345441	1.66914295	7.14255036	2.50821909	2.39109331	0.00090325	0.00023229	0.00042411	0.00155965
1.87212726	1.65939252	8.10666358	2.35710726	2.84840895	0.00102518	0.00021829	0.00041785	0.00166131
1.89128622	1.64834134	9.25337665	2.22570016	2.78924235	0.00117135	0.00020640	0.00040917	0.00178951
1.91091667	1.63900225	10.75239243	2.12054105	2.73456027	0.00135950	0.00019638	0.00039674	0.00195263

EQUIVALENT LOAD LEVELS FOR STEEL GEARS

SMALL SCALE COATED TITANIUM GEARS - TEST DATA - RYDER E = 30.0 * 10**6

δ = .30

effective face width = .25

TEST TIME	RYDER GAUGE	HERTZ STRESS	* * * * * * * * * * *TORQUE *LB IN	NORMAL (LB)	LOAD TANGENTIAL (LB)	* * * * * * * * * * HP	PPI * *	AXIAL TRAVEL	RPM
	2.817	40000.	44.69	28.17	25.53	9.93	112.70	0.00252	14000.
	3.566	45000.	56.56	35.66	32.32	12.56	142.63	0.00318	14000.
	4.402	50000.	69.82	44.02	39.90	15.51	176.09	0.00392	14000.
	5.327	55000.	84.48	53.27	48.28	18.77	213.07	0.00476	14000.
	6.339	60000.	100.54	69.39	57.45	22.33	253.57	0.00566	14000.
	7.440	65000.	118.00	74.40	67.43	26.21	297.59	0.00664	14000.
	8.628	70000.	136.85	86.28	78.20	30.40	345.14	0.00770	14000.
	9.905	75000.	157.10	99.05	89.77	34.90	396.20	0.00884	14000.
	11.270	80000.	178.74	112.70	102.14	39.71	450.79	0.01006	14000.
	12.723	85000.	201.79	127.23	115.31	44.82	508.90	0.01136	14000.
	14.263	90000.	226.22	142.63	129.27	50.25	570.53	0.01274	14000.
	15.892	95000.	252.06	158.92	144.03	55.99	635.69	0.01419	14000.
	17.609	100000.	279.29	176.09	159.59	62.04	704.36	0.01572	14000.
	19.414	105000.	307.91	194.14	175.95	68.40	776.56	0.01733	14000.
	21.307	110000.	337.94	213.07	193.11	75.07	852.28	0.01902	14000.
	23.288	115000.	369.36	232.88	211.06	82.05	931.52	0.02079	14000.
	25.357	120000.	402.17	253.57	229.81	89.34	1014.28	0.02264	14000.
	27.514	125000.	436.39	275.14	249.36	96.94	1100.57	0.02457	14000.
	29.759	130000.	471.99	297.59	269.71	104.85	1190.37	0.02657	14000.
	32.093	135000.	509.00	320.93	290.86	113.07	1283.70	0.02865	14000.
	34.514	140000.	547.40	345.14	312.80	121.60	1380.55	0.03082	14000.
	37.023	145000.	587.20	370.23	335.54	130.44	1480.92	0.03306	14000.
	39.620	150000.	628.40	396.20	359.08	139.59	1584.82	0.03538	14000.
	42.306	155000.	670.99	423.06	383.42	149.05	1692.23	0.03777	14000.
	45.079	160000.	714.97	450.79	408.56	158.82	1803.17	0.04025	14000.
	47.941	165000.	760.36	479.41	434.49	168.90	1917.63	0.04280	14000.
	50.890	170000.	807.14	503.90	461.22	179.29	2035.61	0.04544	14000.
	53.928	175000.	855.32	539.28	488.75	189.99	2157.11	0.04815	14000.
	57.053	180000.	904.89	570.53	517.08	201.01	2282.14	0.05094	14000.
	60.267	185000.	955.86	602.67	546.21	212.33	2410.68	0.05381	14000.
	63.569	190000.	1008.23	635.69	576.12	223.96	2542.75	0.05676	14000.
	66.959	195000.	1061.99	669.59	606.85	235.90	2678.34	0.05978	14000.
	70.436	200000.	1117.15	704.36	638.37	248.16	2817.45	0.06289	14000.

SMALL SCALE COATED TITANIUM GEARS - TEST DATA - HYDRO E = 16.5 x 10**6

δ = .35

effective face width = .250

TEST TIME	HYDRO GAUGE	HERTZ STRESS	TORQUE (LB IN)	NORMAL (LB)	LOAD TANGENTIAL (LB)	HP	PSI	AXIAL TRAVEL	RPM	BENDING STRESS F = .29
	4.940	40000.	78.35	49.40	44.77	17.40	197.59	.00441	14000.	
	6.252	45000.	99.16	62.52	56.66	22.02	250.07	0.00558	14000.	
	7.713	50000.	122.41	77.15	69.95	27.19	308.72	0.00689	14000.	
	9.339	55000.	148.12	93.39	84.64	32.90	373.56	0.00834	14000.	
2.0	11.114	60000.	176.29	111.14	100.73	39.16	444.57	0.00992	14000.	3279.
	13.044	65000.	206.99	130.44	118.22	45.96	521.76	0.01165	14000.	
2.0	15.128	70000.	239.93	151.28	137.10	53.30	605.11	0.01351	14000.	4462.
	17.366	75000.	275.43	173.66	157.39	61.18	694.64	0.01551	14000.	
2.0	19.759	80000.	313.33	197.59	179.08	69.61	790.35	0.01764	14000.	5828.
	22.306	85000.	353.78	223.06	202.16	78.59	892.23	0.01992	14000.	
2.0	25.007	90000.	396.62	250.07	226.64	88.10	1000.29	0.02233	14000.	7377.
	27.863	95000.	441.92	278.63	252.52	98.16	1114.52	0.02488	14000.	
2.0	30.873	100000.	489.66	308.73	279.81	108.77	1234.92	0.02757	14000.	9107.
	34.038	105000.	539.86	340.38	308.49	119.92	1361.50	0.03039	14000.	
10.0	37.356	110000.	592.49	373.56	338.56	131.61	1494.26	0.03335	14000.	11019.
	40.830	115000.	647.57	408.30	370.04	143.85	1633.19	0.03646	14000.	
10.0	44.457	120000.	705.11	444.57	402.92	156.63	1778.29	0.03969	14000.	13114.
	48.239	125000.	765.09	482.39	437.20	169.95	1929.57	0.04307	14000.	
10.0	52.176	130000.	827.52	521.76	472.87	183.82	2087.02	0.04659	14000.	15391.
	56.266	135000.	892.46	562.66	509.95	198.22	2250.65	0.05024	14000.	
10.0	60.511	140000.	959.73	605.11	548.42	213.19	2420.45	0.05403	14000.	17849.
	64.911	145000.	1029.51	649.11	588.29	228.69	2596.43	0.05796	14000.	
	69.464	150000.	1101.73	694.65	629.56	244.73	2778.59	0.06202	14000.	
	74.173	155000.	1176.41	741.73	672.23	261.32	2966.91	0.06622	14000.	
	79.035	160000.	1253.53	790.35	716.30	278.45	3161.40	0.07057	14000.	
	84.052	165000.	1333.10	840.52	761.77	296.13	3362.08	0.07505	14000.	
	89.223	170000.	1415.12	892.23	808.64	314.37	3568.93	0.07966	14000.	
	94.549	175000.	1499.59	945.49	856.90	333.11	3781.95	0.08442	14000.	
	100.029	180000.	1586.50	1000.29	906.57	352.41	4001.15	0.08931	14000.	
	105.663	185000.	1675.86	1056.63	957.63	372.27	4226.53	0.09434	14000.	
	111.452	190000.	1767.67	1114.52	1010.10	392.66	4458.07	0.09951	14000.	
	117.395	195000.	1861.93	1173.95	1063.96	413.60	4695.80	0.10482	14000.	
	123.492	200000.	1958.64	1234.92	1119.22	435.08	4939.70	0.11026	14000.	

APPENDIX II

RYDER GEAR TEST INSPECTION DATA SHEETS FOR HARD COATED, SMALL-SCALE TITANIUM GEARS.

PHASE I

Test No. 1, Gear Set 1-A/B
Test No. 2, Gear Set 2-A
Test No. 3, Gear Set 1/2-B
Test No. 4, Gear Set 3-A
Test No. 5, Gear Set 4-A

PHASE II

Test No. 1, Gear Set 2-A
Test No. 2, Gear Set 2-B
Test No. 3, Gear Set 3/2-A

PHASE III

Test No. 1, Gear Set 1-A
Test No. 2, Gear Set 1-B
Test No. 3, Gear Set 2-A
Test No. 4, Gear Set 3-A
Test No. 5, Gear Set 2-B
Test No. 6, Gear Set 4-A

Test Data—Phase I, Test No. 1,

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
Break-in schedule				
<1	0.14	74,816	56,502	Slight burnish at and below pitch line
<1	0.42	74,816	56,502	Relatively unchanged
1	0.84	74,816	56,502	Bonded lubricant confined to bottom 1/3 of most teeth
2	1.68	81,595	61,640	Unchanged
3	2.52	88,396	66,765	More pronounced wear-in pattern on most teeth
4	3.36	95,220	71,910	Relatively unchanged
5	4.20	102,042	77,043	Narrow gear teeth relatively unchanged; plating bubble or blister on wide gear tooth No. 35 near center below pitch line
Endurance test				
6	5.04	108,829	82,191	No appreciable change on narrow gear; bubble on wide gear tooth partially healed
9	7.56	108,829	82,191	Relatively little change in either gear
12	10.08	108,829	82,191	Same
15	12.60	115,643	87,330	Narrow teeth No. 2 and 34 initiated scuffing below pitch line; approx 1/16-in. area of bubble spalled out on wide tooth No. 35

Test Data—Phase I, Test No. 1, (contd)

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
20	16.80	115,643	87,330	Narrow teeth No. 2 and 34 unchanged; No. 12, 13, 15, and 19 show rust-type stains near front face above pitch line
25	21.00	122,400	92,459	Narrow teeth No. 1,2,3,8,9,13,14,15,17,19,20, 29,33,34, and 36 show slight scoring below pitch line; No. 12, 13, and 18 show rust-type stain near front of tooth above pitch line
30	25.20	122,400	92,459	Narrow teeth No. 2,32,34,35, and 36 showed 11, 4,7,5 and 3% scuffing, respectively; wide tooth No. 35 chipped through the plate on front face; see Figure 53. (A detailed view of the wide gear is shown in Figure 54.)

Test No. 1 terminated

Test Data—Phase I, Test No. 2,

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
Break-in schedule				
<1	0.14	73,754	55,701	Light burnishing affecting approx 1/2 of teeth near front face and 1/2 near rear face
<1	0.42	73,754	55,701	No change
1	0.84	73,754	55,701	No change
2	1.68	80,431	60,744	Narrow teeth No. 21,22,23,24,26,27, and 32 show increased wear pattern above pitch line near rear face; teeth No. 25,28,29,30,31,33,34, 35, and 36 same height near front
3	2.52	87,155	65,822	No change
4	3.36	93,856	70,883	No change
5	4.20	100,557	75,944	Narrow teeth unchanged; wide teeth show rust-type stain near front face of No. 5
Endurance test				
14	11.76	107,276	81,018	Test rig failure caused loss of lubrication. Narrow teeth No. 19,26,28, and 29 cracked

Test No. 2 terminated

Test Data—Phase I, Test No. 3,

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
Break-in schedule				
<1	0.14	75,675	57,152	Nearly all teeth of narrow gear had surface irregularities near the edge breaks at front and rear faces; wide gear was unchanged
<1	0.42	75,675	57,152	No change
1	0.84	75,675	57,152	Rust-type stain appeared on 33 teeth of both gears, primarily near rear face
2	1.68	82,526	62,326	Initiated scuffing near the roots of narrow teeth No. 1,4,11,16,20,24,27,29, and 31, wide gear satisfactory
3	2.52	89,426	67,537	Surface irregularities readily visible on narrow teeth No. 5 through 17 and 32 through 36; wide gear unchanged
4	3.36	96,301	72,729	Narrow gear relatively unchanged, scoring is negligible; wide gear unchanged
5	4.20	103,177	77,922	Narrow teeth No. 5 and 28 showed minor spalling damage to working surface near front edge break; surface irregularities on all other teeth except No. 6 and 33; wide gear unchanged. (See Figure 55 for typical gear tooth wear pattern after 4 million cycles.)
Endurance test				
10	8.40	110,803	83,681	Fracture of narrow teeth No. 12 through 18; see Figure 56. (A detailed view of the narrow gear is shown in Figure 57.)

Test No. 3 terminated

Test Data—Phase I, Test No. 4,

Small-scale gears

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
Break-in schedule				
<1	0.14	74,137	55,990	Excessive tooth wear indicated
<1	0.42	74,137	55,990	Increased wear on all teeth
1	0.84	74,137	55,990	Increased wear on all teeth
2	1.68	80,881	61,084	Increased wear on all teeth
2.5	2.10	87,618	66,171	Approx 50% of teeth showed misaligned tooth wear pattern

Test No. 4 terminated

Note: The test gears were reground to have 0.005-in. average coating thickness. When shotpeened, the coating came off in the nickel-rich areas of the tooth flanks; the gears were not suitable for retesting.

Test Data—Phase I, Test No. 5,

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
Break-in schedule				
:10	0.14	74,146	55,997	Narrow teeth No. 23 and 27 show nicks at tips; wide gear unchanged
:30	0.42	74,146	55,997	Narrow teeth No. 3, 23, and 27 show nicks at tips; wide gear unchanged
1	0.84	74,146	55,997	Unchanged
2	1.68	80,859	61,067	Narrow tooth No. 32 scored at tip; wide gear unchanged
3	2.32	87,619	66,172	Narrow tooth No. 27 chipped through plate at OD for two-thirds face widths from front side; wide gear unchanged
4	3.36	94,353	71,260	Narrow teeth No. 6, 27, and 36 chipped through plate at OD one-third, three-fourths, and two-thirds of face width; wide gear unchanged
5	4.20	101,092	76,348	Narrow teeth No. 8 and 32 chipped through plate at OD two-thirds and three-fourths of face width; wide gear unchanged

Test Data—Phase I, Test No. 5, (contd)

Time (hr)	Accumulated cycles (millions)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
Endurance Test				
6	---	114,583	86,537	Narrow teeth No. 1, 4, 5, 6, 8, 10, 27, 30, 32, 33, 35, and 36 had broken tips through iron plate at OD; wide gear unchanged
7	---	114,583	86,537	Length and width of tip breakage gradually increasing; wide gear unchanged
10	---	114,583	86,537	Additional broken tips on narrow teeth No. 25 and 34; wide teeth No. 33 and 35 show axial cracks near tip
11	---	134,793	101,800	Narrow gear shows wear and scoring near root of some teeth; broken tip on tooth No. 35
13:30	---	134,793	101,800	Additional broken tips on narrow teeth No. 2, 14, and 24—also increased scoring and wear; additional broken tips on wide teeth No. 30 and 32
16	---	134,793	101,800	Axial crack near tip of narrow tooth No. 3, no other change; wide gear unchanged
17	---	153,236	115,729	Additional broken tips on narrow teeth No. 3, 11 and 12—also approx one-third of tooth No. 36 missing; additional broken tips on wide teeth No. 1,4,5,28, and 29
17:24	---	173,228	130,827	Complete loss of narrow tooth No. 34 (root fracture), additional broken tips on teeth No. 9 and 16, scoring ranged between 6 and 34%; wide gear relatively unchanged

Test No. 5 terminated

Test Data—Phase II, Test No. 1,

Time (hr)	Accumulated cycles (X 10^6)	Hertz stress (psi) Steel	Titanium	Condition of the gear teeth
1	0.14	79,430	60,000	Slight burnishing below pitch line on most teeth, wear-in pattern
1	0.84	79,430	60,000	No change
2	1.68	79,430	60,000	Wear-in pattern slightly more pronounced, no scuffing
4	3.36	92,650	70,000	No change
6	5.04	105,910	80,000	Wear-in pattern indicates some misalignment of gears; test terminated before any observable damage to gear teeth

Test Data—Phase II, Test No. 2,

Time (hr)	Accumulated cycles (x 10^6)	Hertz stress (psi) Steel	Titanium	Condition of the gear teeth
1	0.14	79,430	60,000	Slight burnishing below pitch line on most teeth, normal wear-in pattern
1	0.84	79,430	60,000	No change
2	1.68	79,430	60,000	Wear-in pattern slightly more pronounced, no scuffing
4	3.36	92,650	70,000	No change
6	5.04	105,910	80,000	Narrow No. 7-19: fretting stains no change in wear-in pattern
8	6.72	119,155	90,000	N 8-12, 15-17, 19, 20: fretting stains. Indication of light scuffing above pitch line on numerous teeth
10	8.40	132.385	100,000	N 4-20: fretting stains; no increase in scuffing patterns
Endurance Test				
12.5	10.50	145,640	110,000	N 3-19: fretting stains; N 6, 12, 15, 19: axial cracks above pitch line. N 7: plating missing from tip of tooth. The test terminated before further damage to narrow gear. No damage observed on wide gear

Test Data—Phase II, Test No. 3,

Time (hr)	Accumulated cycles ($\times 10^6$)	Hertz stress (psi) Steel	Titanium	Condition of the gear teeth
Break-in schedule				
L-1	0.14	79,430	60,000	Narrow No. 1: small pit above pitch line, right side. Narrow No. 9 - 12, 14, 18: axial cracks above pitch line. Narrow gear 14, 18: fretting stains
1	0.84	79,430	60,000	N 1: no change N 4-14, 18: axial cracks N3, 11, 12, 14, 15; fretting stains
2	1.68	79,430	60,000	N 1: no change N 4-14: axial cracks N 1-21: fretting stains N 11-15, 18, 19: contact in root area
4	3.36	92,650	70,000	N1: no change N 4-14, 17, 18: axial cracks N 3-7, 11, 13: fretting strains
6	5.04	105,910	80,000	N 1: no change N 4-14: axial cracks N 1-14, 21. fretting stains
8	6.72	119,155	90,000	N 1: no change N 4: small chip of plate missing from right margin above pitch line N 4-14: axial cracks N 1-14, 21: fretting stains
10	8.40	132,385	100,000	N 1: no change N 4: no change N 4-14: axial cracks N 1-14, 21: fretting stains
Endurance				
12.3	10.33	145,840	110,000	Test terminated because of loss of plating from all narrow and wide teeth

Test Data—Phase III, Test No. 1,

Time (hr)	Accumulated cycles (X 10^6)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
<1	0.14	79,430	60,000	Some burnishing below PD
1	0.84	79,430	60,000	Test gear wandered on drive shaft after the zero-torque drive shaft nut backed off. Plating on gear teeth appears to be distressed, but not considered to be scuffing damage

Test No. 1 Terminated

Test Data—Phase III, Test No. 2,

Time (hr)	Accumulated cycles (X 10^6)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
<1	0.14	79,430	60,000	Plate cracked on four teeth after the zero-torque drive shaft nut again backed off

Test No. 2 Terminated

Test Data—Phase III, Test No. 3,

Time (hr)	Accumulated cycles (X 10^6)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
<1	0.14	79,430	60,000	Light burnishing below PD
<1	0.28	79,430	60,000	No change
<1	0.42	79,430	60,000	No change
1	0.84	79,430	60,000	No change
2	1.68	79,430	60,000	No change
4	3.36	92,650	70,000	No change
6	5.04	105,910	80,000	No change
8	6.72	119,155	90,000	No change
10.0	8.40	132,385	100,000	Teeth 8-13 show initial scuffing (0.6%)
12.5	10.50	145,640	110,000	Significant scuffing all teeth; heaviest on 5, 7-12, 21 (21%). Test oil flow increased to 1600 ml/min., auxiliary oil cooler installed
13.7	11.51	145,640	110,000	Minor scuffing increase to .23%

Test Data—Phase III, Test No. 3

Time (hr)	Accumulated cycles (× 10^6)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
15.0	12.60	145,640	110,000	Minor scuffing increase to 25%
17.5	14.70	145,640	110,000	No change
20.0	16.80	145,640	110,000	Scuffing increase to 29%
21.2	17.81	158,875	120,000	Scuffing increase to 33%
22.5	18.90	158,875	120,000	No change
23.5	19.74	158,875	120,000	No change
25.0	21.00	158,875	120,000	Moderate increase in scuffing (36%)
27.5	23.10	158,875	120,000	Cracked plating on tooth No. 7. Moderate increase in scuffing of other teeth (40%)

Test suspended briefly, and then restarted after nondestructive metallurgical examination.

27.7	23.27	158,875	120,000	Cracked plating on tooth No. 7 shows burnishing. No increase in average scuffing rate (40%)
29.2	24.53	158,875	120,000	Cracked plating on tooth No. 7 separated along left edge. Face of mating tooth on driven gear shows heavy damage, and adjacent teeth show extensive scuffing. Average scuffing of teeth on test gear shows sudden increase (75%)

Test No. 3 Terminated

Test Data—Phase III, Test No. 4

Time (hr)	Accumulated cycles (× 10^6)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
<1	0.14	79,430	60,000	Gear teeth were honed prior to lube coating. Average scuffing was 5% after initial run.
<1	0.42	79,430	60,000	No change
1	0.84	79,430	60,000	No change
2	1.68	79,430	60,000	No change
4	3.36	92,650	70,000	No change
6	5.04	105,910	80,000	No change
8	6.72	119,155	90,000	Average scuffing was 6%
10	8.40	132,385	100,000	No change

Test Data—Phase III, Test No. 4, (contd)

Time (hr)	Accumulated cycles ($\times 10^6$)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
15	12.60	145,640	110,000	No change
19.5	16.38	145,640	110,000	Testing was interrupted when the instrumentation indicated a sudden change in the gear operation. Visual examination revealed that the test gear had fractured from the root radius between teeth No. 6 & 7 to the root radius of a spline at the gear hub

Test No. 4 Terminated

Test Data—Phase III, Test No. 5

Time (hr)	Accumulated cycles ($\times 10^6$)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
<1	0.14	79,430	60,000	Gear teeth were honed prior to lube coating. Average scuffing after initial run was 2%
<1	0.42	79,430	60,000	No change
1	0.84	79,430	60,000	No change
2	1.68	79,430	60,000	Average scuffing was 4%
4	3.36	92,650	70,000	No change
6	5.04	105,910	80,000	No change
8	6.72	119,155	90,000	No change
10	8.40	132,385	100,000	Average scuffing was 5%
12.5	10.50	145,640	110,000	Average scuffing increase to 9%
20.0	16.80	145,640	110,000	Average scuffing was 11%
21.7	18.19	158,875	120,000	Testing was interrupted when the instrumentation indicated a sudden change in gear operation. Visual examination revealed that test gear tooth No. 7 had fractured from the gear. The broken tooth did not appear to be deformed. The average scuff rate on the remaining 20 teeth was 17%

Test No. 5 Terminated

Test Data—Phase III, Test No. 6

Time (hr)	Accumulated cycles (X 10^6)	Calculated surface stress levels (psi) Steel	Titanium	Condition of gear teeth
<1	0.14	79,430	60,000	Gear teeth were honed and black oxide coated; no lube coat was applied. Gear teeth showed only some burnishing after initial run
1	0.84	79,430	60,000	Average scuffing was 2%
2	1.68	79,430	60,000	Average scuffing was 3%
4	3.36	92,650	70,000	No change
6	5.04	105,910	80,000	Average scuffing was 4%
8	6.72	119,155	90,000	Visual examination revealed that approximately 25% of the plate on the face of No. 18 tooth was missing. The average scuffing of the other teeth was still 4%

Test No. 6 Terminated

APPENDIX III

GEAR MANUFACTURING PROCESS ROUTING

ROUTE SHEET

Sheet 1 of 9 — Part No. EX72251

Part Name: Titanium Hydro Test Gear — Process Eng.: Phillips — Date: 2-23-72

Material Spec. & Size: 6Al-2Sn-4Zr-6Mo-6 w/2 dia x 5/8 thk.

Drawing Part No.: EX72251

Oper.	Line Count	Dept.	Work Center	Tool No. / Operation Description	Set-up Time	Estimated Hours
10		Shop		Start folder on each part & forward to Dept. 802 for verification.		
20		802		Start record & verification.		
30		8565		Machine per sketch oper. 30 & break edges.	8.0	3.0000
40		1-925		Grind faces per sketch oper. 40 & break edges.	.5	.5000
50		8581		Grind faces per sketch oper. 50 & break edges.	8.0	.5000

ROUTE SHEET

Sheet 2 of 9 — Part No. EX72251

Process Eng.: Phillips — Date: 2-23-72

Drawing Part No.: EX72251

Oper.	Line Count	Dept.	Work Center	Tool No. / Operation Description	Set-up Time	Estimated Hours
60		8528		5-22648 Arbor Grind OD per sketch oper. 60 & break edges.	1.0	.5000
70		8540		5-17225 Hob 11172-3 Arbor Rough hob gear to 3.375 ±.002 dia. over (2) .288 dia. pins. Hold root dia. to 3.150 ±.005 dia. Hob more than (1) piece at a time.	2.0	1.0000
80		8545		5-17324 Adapter Finish cut internal spline. Caution: Note alignment of spline with gear teeth. Mark spline space used for alignment.	2.0	2.0000

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ROUTE SHEET

Sheet 3 of 9

Part No.	EX[illegible]
Drawing Change	Phillips
Date	2-23-72
Drawing Part No.	EX[illegible]

Oper.	Dept.	Tool No. / Operation Description	Set-up Time	Estimated Hours
90	[illegible]	[illegible] Arbor	[illegible]	[illegible]
		Grind Gear OD to [illegible] dia.		
		Caution: [illegible]		
100	[illegible]	Break edges of spline teeth .010		[illegible]
110	[illegible]	[illegible] Gear Form	4.0	4.[illegible]
		[illegible] Arbor		
		Grind Gear to [illegible] dia. over [illegible] dia. pins.		
		Grind [illegible] dia. to [illegible] dia.		
		Caution: [illegible]		
		with [illegible] spline [illegible]		
		Center with [illegible] arbor.		
120	[illegible]	Break edges & tips of gear teeth .020 – .030		5.[illegible]

ROUTE SHEET

Sheet 4 of 9

Part No.	EX7225I
Drawing Change	Phillips
Date	2-23-72
Drawing Part No.	EX7225I

Oper.	Dept.	Tool No. / Operation Description	Set-up Time	Estimated Hours
130	546	[illegible] Dept. 5577 Attn: O. Shockley		
		Plate .292 thick minimum.		
140	5577	Glass bead peen per ES 12216		
		No. 31 13 [illegible] 45° pressure.		
150	827	Vacuum diffusion bond at 1600°F for 3 hours.		
		(Attn: [illegible] Colored)		
160	EI974	Magnetic Inspection.		
170	2525	Grind faces per sketch oper. 170 & break edges.	1.0	3.0000

ROUTE SHEET

Sheet 5 of 9

Part No. [illegible]

Planner: Phillips — Date: 2-23-72

Manufacturing Part No. [illegible]

Oper.	Line Comp.	Dept.		Tool No. / Operation Description	Set-up Time	Estimated Hours
180		[illegible]		8-27948 Arbor	1.0	.3000
				Grind (2) per sketch oper. 180 & break edges.		
				Caution: [illegible] total number of teeth while grinding.		
190		356		570-2926 Gear Former	4.0	4.0000
				8-27292 Arbor		
				Grind gear to [illegible] dia. over (2) .288 dia. pins.		
				[illegible] on arbor on [illegible] spline gage on pin on arbor.		
				[illegible] with pin on arbor [illegible] equal amount of [illegible] on both sides.		
				Hold root dia. to [illegible] dia.		
200		356				.5000
				Break edges of gear teeth [illegible]		
				Break tips of gear teeth [illegible]		
205		[illegible]		Ultrasonic Inspect [illegible]		

ROUTE SHEET

Sheet 6 of 9

Part No. [illegible]

Planner: Phillips — Date: 2-23-72

Oper.	Line Comp.	Dept.		Tool No. / Operation Description	Set-up Time	Estimated Hours
210		[illegible]		Magnaflux.		.2000
215				Glass Bead Peen. #13 Glass & 40 psi.		
220		846		PO BC 5 Dept. 5527 Att. Phil Collard for carbonitride.		
				Glass Bead Peen per [illegible] No. [illegible] Sec 45° Pressure.		
				Carbonitride.		
				Glass Bead Peen per [illegible] No. [illegible] Sec 45° Pressure.		
230		[illegible]		Magnaflux		.2500
240		[illegible]		Machine Groove per Sketch Oper. 240 & Break Edges.	1.5	1.5000

ROUTE SHEET

Sheet 7 of 9

Part No. EX0[illegible]

Process Chan: Phillips | Date: 2-23-72

Shipping Part No. EX0[illegible]

Oper.	Line Count	Dept.	Code	Operation Description	Set-up Time	Estimated Hours
250		[illegible]		Grind Form per Sketch Oper. 250 & Break Edges.		.5000
260		[illegible]		Grind Bore & 2.000 – 1.999 dia. (2) Form & Adj. Form per Sketch Oper. 260 & Break Edges.	8.0	2.5000
270		[illegible]		S-[illegible] Arbor	.5	.5000
				Grind OD per Sketch Oper. 270 & Break Edges.		
280		854		S[illegible] Gear Grinding	4.0	4.[illegible]
				S-20256 Arbor		
				Finish Grind Gear [illegible] dia. Over (2) .288 dia. Pins		
				[illegible]		
				[illegible]		
				[illegible] dia.		

ROUTE SHEET

Sheet 8 of 9

Part No. EX0225[illegible]

Process Chan: Phillips | Date: 2-23-72

Shipping Part No. EX0225[illegible]

Oper.	Line Count	Dept.	Code	Operation Description	Set-up Time	Estimated Hours
290		854		Break Edges of Gear Teeth .010 – .020.		.5000
				Break Tip of Gear Teeth .005 max.		
300		846		RPO BCS Dept. 5527.		
				Glass Sand Bead per ES 12256 No. 51-53 Size 40[illegible] Pressure		
310		E[illegible]		Fluorescent Inspect.		.2000
320		E[illegible]		Inspect for Coating (Nodule Coat)		
330		846		RPO BCS Dept. 5527.		
				Lube Coat per ES 11722.		

ROUTE SHEET

SHEET 9 OF 9

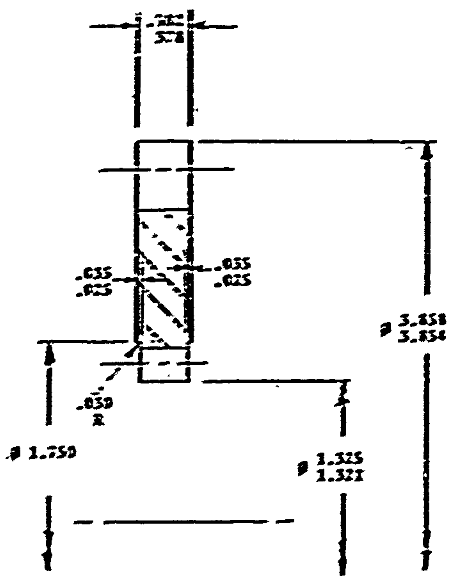
Phillips

5-23-72

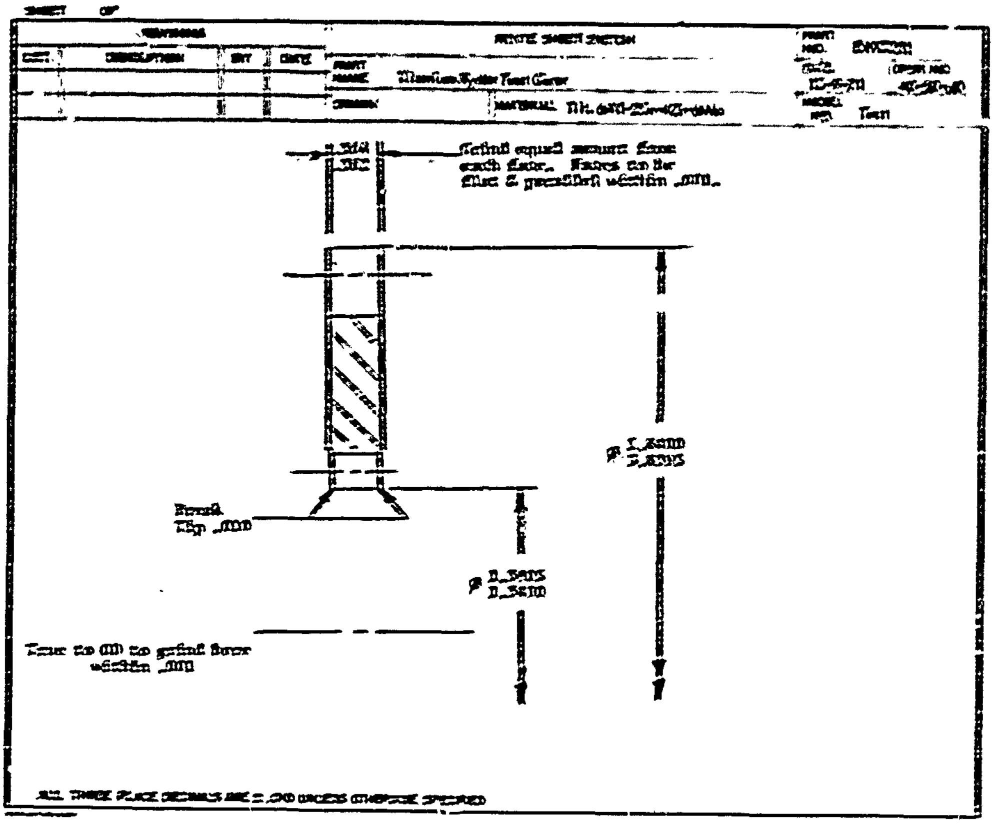
OPER	DEPT		
280		Inspect & Identify	
		Mfg. 27.0	
		Sub. 24.0	
		Insp. 3.3	

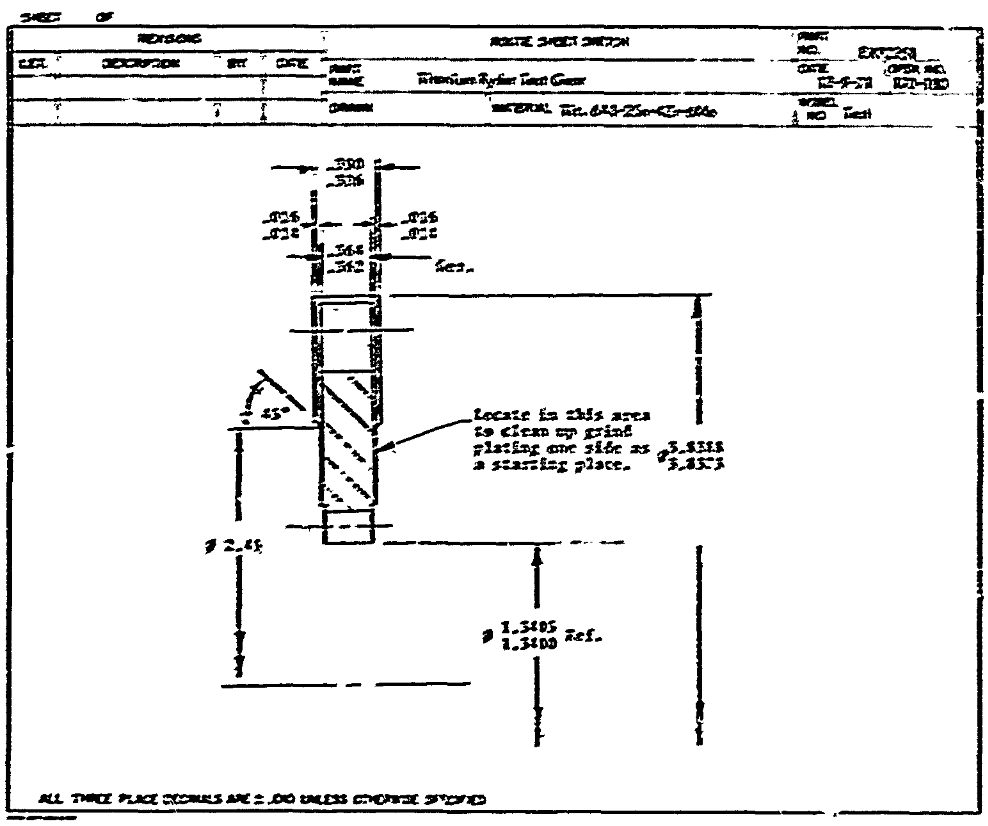
SHEET OF

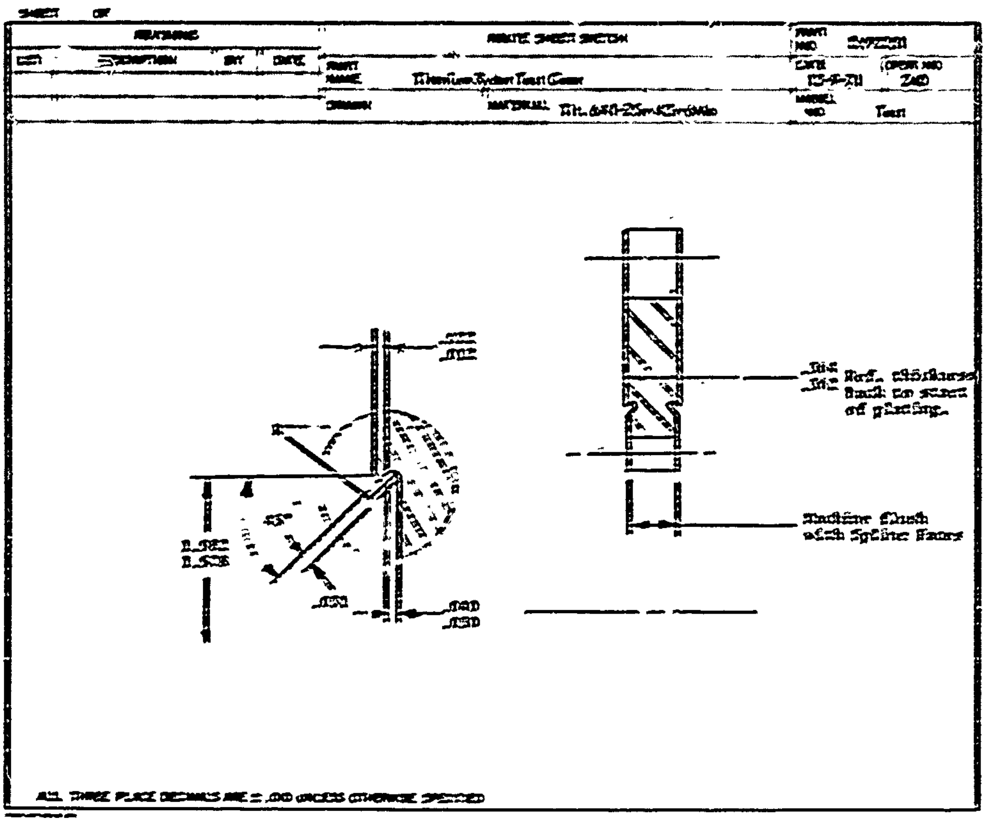
REVISIONS	ROUTE SHEET SKETCH	
LTR. / DESCRIPTION / BY / DATE	PART NAME Titanium Ryder Test Gear	DATE 12-9-71 / OPER NO. 30
	DRAWN / MATERIAL Ti. 6Al-2Sn-4Zr-6Mo	MODEL NO. Test

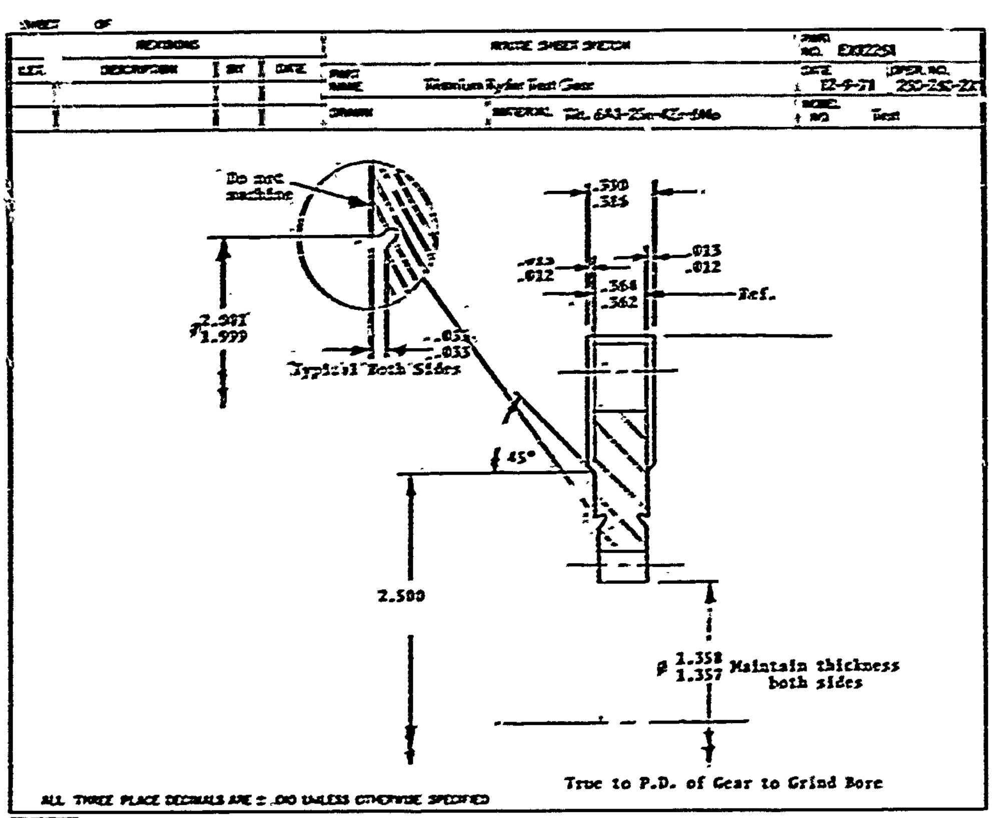


ALL THREE PLACE DECIMALS ARE ± .010 UNLESS OTHERWISE SPECIFIED


SHEET OF
ROUTE SHEET SKETCH
Titanium Ryder Test Gear
Test
.364
.362
ϕ .5405
.5400
ALL THREE PLACE DECIMALS ARE ± .010 UNLESS OTHERWISE SPECIFIED


SHEET OF
REVISIONS
ROUTE SHEET SKETCH
DESCRIPTION
Titanium Ryder Test Gear
Test
.330
.326
.016
.012
.016
.012
.364
.362
Ref.
Locate in this area
to clean up grind
plating one side as
a starting place.
45°
ϕ 2.45
ϕ 1.3405
1.3400 Ref.
ALL THREE PLACE DECIMALS ARE ± .010 UNLESS OTHERWISE SPECIFIED


ROUTE SHEET SKETCH
45°


ROUTE SHEET SKETCH
Titanium Ryder Test Gear
Do not machine
.330
.325
.013
.012
.364
.362
Ref.
Typical Both Sides
45°
2.500
1.358
1.357
Maintain thickness both sides
True to P.D. of Gear to Grind Bore
ALL THREE PLACE DECIMALS ARE ± .010 UNLESS OTHERWISE SPECIFIED